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(6) INVESTIGATION OF THE SUITABILITY OF THE OPEN-CELL TYPE OF BATTERY VENTILATION FOR USE ABOARD SUBMARINES,

(10) J. J. Lander,

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Approved by:

J. C. White - Head, Electrochemistry Section

Dr. Parry Borgstrom
Superintendent - Chemistry Division

Rear Adm. A. H. Van Keuren, USN (Ret)
Director, Naval Research Laboratory

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NRL Problem P-12

ABSTRACT

~~Work has been done in the~~ development of a system of ventilation of submarine storage batteries ~~employing~~ cooling through the cell lugs, for the purpose of replacing, if possible, the present ventilation system * ~~which has many disadvantages~~. Measurements of cell temperatures under a variety of conditions using the system developed and the present closed-cell system h~~ave been~~ were made. ~~for purposes of comparison, and it has been~~ It was found that under ordinary conditions of ambient temperature the proposed system should be either equal to or better than the present system in cooling efficiency.

The proposed system ~~has been shown to~~ can cut the water-loss from the cells to small fraction of the amount lost under the closed-cell system.

~~The proposed method~~ It enables the cell to be completely sealed, except for a small vent hole, thus preventing acid spray and electrolyte spillage.

An "open-type" system of ventilation employing induced air flow through the cell top h~~as been found~~ feasible but less practical than the proposed system.

Cooling through the sides of the cell h~~as been~~ was studied ~~to a small extent and indicates~~ and it appears that cooling by this means would be a good supplement to any system used~~, at least for certain types of cells~~.

Suggestions are made for ~~further~~ increasing the cooling efficiency of the proposed system ~~by changes in design~~.

* is discussed. This system employs

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I. INTRODUCTION

A. Authorization

1. This investigation was authorized by BuShips ltr SS/S62-4(330), dated January 1943.

B. Statement of Problem

2. In accordance with BuShips ltr SS/S62-4(330), this problem was undertaken to investigate the suitability of the open-type system of battery ventilation for use aboard submarines. "Open-type" system has not been strictly defined, but by common usage might mean any system which ventilates the individual cells directly into the space above the battery in the battery compartment. Such a definition would distinguish it from the present closed-type system which ventilates the cells by means of an air manifold into some other part of the ship.

3. Investigation of any system of ventilation of submarine batteries breaks down into the following factors:

(a) Cell temperature.
(b) Water-loss from the cells.
(c) Explosion hazards due to the battery gases.
(d) Acid spray or mist and electrolyte spillage.
(e) Cell design and battery operation methods.

Any system which might be developed would have to compare favorably with the present closed-type system, considering the above factors, in order to enable or justify a change from one type to another.

C. Known Facts Bearing on the Problem

4. Submarines are frequently required to operate in tropical waters where the high ambient temperatures cause the batteries to run at high temperatures with attendant high water-loss from the cells, decreased life of the cells, discomfort to the personnel, or extra load on the air conditioning system as a result of water-loss from the cells. Of these, the chief reason for cooling the batteries is that the high temperatures have a definite effect in materially shortening the life of the cell. In addition, the water-loss decreases the efficiency of the ship by making necessary the operation of distillation apparatus, and the use of man-hours in watering the cells. It has been reported that it may take two men as much as one and one-half hours every other day to water the cells. The difficulty in keeping the air-flow uniform over a battery of many cells may result in acid being sucked into the duct system resulting in electrical grounds and self-discharge of the cells, and general trouble in the upkeep of the system. All these effects are present to a lesser degree in northern latitudes where sea-water temperatures are lower. A system of battery

ventilation which would eliminate or decrease these drawbacks, would contribute in an appreciable degree to the comfort and efficiency of the ship.

D. <u>Prior Work on the Problem</u>

5. No very great amount of work has been done previously on the development of a system of ventilation which would either enable the elimination of the present closed-cell system or show that it is most suitable for submarine use.

6. In 1941 the battery ventilation system of the British submarine H.M.S. Truant was studied (reference (a)), to determine hydrogen concentration in a battery tank using open-cell ventilation. The results indicated that that type ventilation could be safely used and that water-loss in such a battery would be smaller than in one using the closed-type system of ventilation, but no unqualified conclusion was warranted from the study.

7. In 1943 the battery ventilation system of the French submarines SS Amazone and SS Archimede were studied (reference (c)), for the same general purpose as was the British submarine previously and the same general conclusions were arrived at. In addition it was reported that the open-cell system be applied to the "step" type batteries in which the longitudinal rows of cells are on different levels with the centerline rows on the lowest level as well as to batteries with cells on the same level as on the British ship. Also on the French ships sufficient space is left between the adjacent cells to allow ample circulation of air over the whole surface of the cell. This is in contrast to British and American practice and may be partially responsible for the lower operating temperatures of the French submarine batteries.

8. A comparison of the closed-cell system with an open-cell system was made aboard the submarine O-6 in 1942 (reference (b)). The forward battery was left intact while the ducting was removed from the after battery which was then ventilated by blowing air over the tops of the cells. It was found that the battery under open-cell ventilation operated hotter than the battery under closed-cell ventilation, while the water-loss was less in the former. The hydrogen concentration was maintained below 2% in the after battery compartment, but the average concentration in the individual cells ran about 13%, which is well above the lower explosive limit of hydrogen in air or oxygen. The report stated that although the concentration in the individual cells was 13%, the possibility of an explosion originating in a cell was so remote as to be negligible.

9. Open-cell ventilation was studied for the purpose of minimizing explosion hazards (reference (e)). In this work a cell was set up with the duct system removed and a stream of air passed over the cell at various velocities, with cell gassing at the finishing rate and ventilating through

the central hole into the air stream above the cell. The concentration of hydrogen in the cell was measured and it was concluded that if the central hole were large enough the concentration could be kept below the explosive limit, and it was recommended that further studies be made of induced ventilation in the cell top.

10. References (b) and (e) sum up the advantages and disadvantages of both types of ventilation as follows:

1. Closed-Cell Ventilation

Advantages.

(a) When the sytem is functioning correctly there is no possibility of an explosive mixture being present anywhere in the system.

Disadvantages.

(a) Complexity necessary to secure a uniform flow through all the cells in a battery.

(b) Corrosion of blower fans.
(c) High water-loss.
(d) Maintenance.
(e) Cost.
(f) Use of a strategic material-rubber.
(g) Loss in man-hours in manufacture and installation of ducts.
(h) An estimated 25% of the tonnage of the air-conditioning equipment is used in dehumidification.
(i) The possibility of derangement of the duct system by depth charges.
(j) The possibility of electrostatic charges in the duct system being a source of explosions.

2. OpenCell Ventilation

Advantages.

(a) Simplicity of design, installation, and maintenance.
(b) Safety because of absence of ducts.
(c) Reduction in water-loss.
(d) Increased cooling by sweeping air around the cell.
(e) Lower cost by eliminating the duct system.

Disadvantages.

(a) The possibility of an explosive mixture being present in the individual cells.

(b) Acid spray and electrolyte spillage.

11. A series of other reports (reference (f) through (i) have been prepared, which, while they are not directly concerned with open-cell ventilation, do bear on the problem because they present studies of the sources of heating in the cells, some cooling effects, and water-loss under various conditions. Some of the conclusions which have been arrived at in these reports and which apply to this work are as follows:

Natural Heating Effects in the Cell are:

(a) Heating due to the chemical reaction which takes place on charge.

(b) I^2R drop through the cell.

(c) Heat of formation of molecular hydrogen and oxygen.

A Natural Cooling Effect is:

(a) Reversal of the reaction:

$$H_2 + \frac{1}{2} O_2 \longrightarrow H_2O + 68.4 \text{ kilogram of calories of heat.}$$

Ventilating air is unimportant in cooling either by evaporation of water or conductance.

There is little temperature variation throughout the cell during the charge. The maximum differential is 8°F. Gassing equalizes temperature throughout the cell.

Cooling due to radiation is negligible.

Water-loss is by far the most important factor in cooling the cell by closed-cell ventilation.

Water-losses increase with higher air temperatures and with decreased humidity. Under some conditions the cell can actually pick up water from the air.

Low temperatures minimize gassing.

12. The foregoing sums up the work which has been done or bears on the problem of this report.

E. <u>Theoretical and Practical Considerations</u>

13. These aspects of the problem will be considered in the order in which they were presented in the statement of the problem.

1. Cell Temperature.

14. The theory of heating and cooling effects which take place naturally in the cell due to the chemical reactions concerned have been quite thoroughly covered in references (f), (h), and (i). This report is primarily concerned with artificial method of cooling the cell. The general possibilities are these:

Internal.

(a) Evaporation of water from the electrolyte.
(b) Cooling by heat exchange to the ventilating air.
(c) Some sort of liquid internal cooling system .

External.

(a) By heat exchange to the air passing over the bottom, top, and sides of the cell.
(b) By heat exchange to the air passing over the busses connecting the cells.
(c) Radiation from all these surfaces.
(d) Some sort of external liquid cooling system.

15. Of these possibilities, internal or external liquid cooling systems appear to be ruled out because of practical difficulties involved and because it would mean replacing a complicated air flow system with a complicated plumbing system. By means of the theoretical equations of heat transmission and the physical constants concerned, the possibilities of the remaining factors in cell cooling should be possible of evaluation, at least roughly, for purpose of comparison.

16. Suppose, for purposes of calculation, a cell (a Gould OWTX-49 with 1250 specific gravity electrolyte) is assumed to be at a temperature of 125°F. with the surroundings at 90°F. What are possible magnitudes of the cooling effects? Appendix I contains the calculations made with their assumptions and limitations. Summing up the results of these calculations, it is found that the quantities of heat lost are 566, 478, 175, 32, and less than 22 kilogram calories per hour by cooling through the sides, the lugs, by evaporation of the electrolyte, heat exchange to the ventilating air, and by radiation from the cell, respectively. The heat loss through the sides and lugs represents the maximum possible for the temperature conditions assumed because they were made on the basis of 100% efficiency of either system. Heat loss by evaporation and interchange to the ventilating air could possibly be greater, but not in any case by more than a factor of four if 100% efficiency is assumed. Since the calculations are admittedly limited by many assumptions and were made for only one set of temperature conditions, they cannot be quantitatively comparable. However, they do show definitely that cooling by radiation must be a negligible effect and is not worth investigation. They indicate that in the present system of closed-cell ventilation, cooling by heat exchange

to the air passing through the cell is probably a small effect compared to heat loss by evaporation. Finally, they indicate that cooling through the lugs and the sides by circulating air over the cell top and around the sides are methods worth investigating and might prove to be better means of cooling the cell than the means utilized by the present system, i.e., evaporation of water and heat exchange to the ventilating air.

2. Water Loss.

17. One of the biggest drawbacks to the present system of closed-cell ventilation is the high rate of water-loss from the cells. If the calculations made previously are really indicative of the possibilities for cooling, then it may be possible to cut down the water-loss considerably by taking advantage of other means of cooling. The factors which might affect the water-loss under the present system are electrolyte temperature and specific gravity, rate of air flow through the cell, temperature and humidity of the input air, whether or not the cell is gassing, and the design of the ventilation system in the individual cell. By varying and controlling these factors water-loss could be decreased to some extent; however, any decrease in water-loss under the present system of ventilation must result in decreased efficiency of cooling, if evaporation is the primary factor in cooling as is indicated by the previous calculations.

18. The ultimate saving in water-loss would be approached by the condition where the cell top is sealed except for a small vent hole for gas escape. By this means it would seem possible to cut the water-loss almost to that minimum necessary because of electrolysis during the gassing phase.

3. Explosion Hazards.

19. Hydrogen and oxygen combine with explosive violence to form water. Inflammation of the mixture has been found to take place (reference (k) pps. 12 and 20) at concentrations from 4 to 8% of hydrogen in air and 4% in oxygen, and up to 74% hydrogen in air and 96% hydrogen in oxygen. Above about 8% the burning takes place with explosive violence. Since the cells give off hydrogen and oxygen during the gassing phase of the charge, and hydrogen on stand, the possibility of explosion must be considered in any system of ventilation which may be used. The present system of ventilation eleiminates the possibility of explosion by ventilating so thoroughly that an explosive mixture could never be present if the system is functioning correctly.

20. Reference (e) considers these possibilities in eliminating the explosion hazard: (a) preventing the generation of the gases, (b) destroying the gases generated by recombination in the cell, (c) diluting the gases until no explosive concentration could be present. The reference states that there is no known method for (a). This is true as long as it is necessary to include the gassing phase in the charge and as long as the lead-acid battery self discharges. The reference also states that investigations along the line of (b) showed no feasible method of obtaining the desired result. (c) is of course the method utilized by the

present ventilation system.

21. However, in addition to these there is another possibility. Theoretical studies (reference (l)) have shown that the explosive reaction can be inhibited by many kinds of surfaces, among them being glass. The reaction may be slowed down to such an extent, under some conditions, that it no longer occurs with explosive violence. Following this line of attack it has recently been demonstrated (reference (m)) that by packing a gas container to a density of two to three pounds per cubic foot with a type of glass wool, the reaction between hydrogen and air may be prevented completely, and that smaller pack densities inhibit the reaction to a great extent. This puts a new light on the ventilation problem for submarine cells, for if investigations could show that the reaction between hydrogen and oxygen could be stopped entirely or inhibited to an extent where it is no longer dangerous, then the necessity for ventilation for the purpose of preventing explosions could be done away with. The cells might be sealed up entirely except for a small hole for gas escape - much like the automobile battery is sealed - with the consequent saving in water as discussed previously.

4. Acid Spray and Electrolyte Spillage.

22. During the gassing phase of the charge, and to a much less extent at other times, breaking bubbles at the electrolyte surface throw acid spray into the air stream. In the present system this may be carried through the ducts and result in corrosion difficulties. In an open-cell system such as in use on British submarines this could be a great source of annoyance to personnel and could cause corrosion of surfaces with which the ventilating air comes in contact. Thus any system must consider the possibility of eliminating this spray. The present system apparently takes care of this to a large extent by baffles and traps, and what does get through is deposited in the engine room where it is burned up in the motors.

23. Electrolyte spillage would not be expected to be a source of difficulty in the present system because the cells are completely closed, however, in any open system spillage due to pitch and roll and resultant splashing might amount to quite a problem.

24. If the explosion investigations should show the presence of glass wool in the cell top to be desirable, the glass wool might act as a very efficient spray trap or baffle and as a damper for electrolyte splashing. If the cell could be sealed up completely except for a small vent hole it would allow the incorporation of a non-spill feature in the cell top such as is used in many smaller batteries today.

5. Cell Design and Operating Methods.

25. The present cell design would appear to be far from efficient from the cooling standpoint. It is a long rectangular cell with

practically all of the cooling under service conditions taking place at the top of the cell. At all times, except during the short gassing phase of the charge when there is considerable stirring, cooling depends on diffusion and convection of the electrolyte and heat conductance by the electrolyte and the grids for bringing the heat to the top of the cell. Diffusion and natural convection are poor methods of heat transfer at best, and lead is a poor conductor of heat as metals go, so if it is important enough to keep the cell cool, changes in design are worth consideration.

26. The calculations made previously indicate that considerable heat may be transferred out of the cell through the sides and up through the shoulders and the lugs. It might be desirable to consider changes in design of the cell case and the lug-shoulder system to develop these means of heat transfer to their most efficient extent.

27. During the ordinary cycle the cell would be on charge approximately eight hours, with forty-five to sixty minutes of this time occupied by the gassing phase. The discharge may take any length of time depending on the needs of the submarine at the time. The discharge reaction utilizes heat from the cell resulting in a cooling effect. At discharge rates above 1000 to 1200 amperes (for the Gould OWTX-49) the I^2R losses overbalance this cooling effect and heating occurs. Apparently nothing can be done about the discharge, but ordinarily the greatest amount of heating will take place during the charge part of the cycle. Thus the investigation of the best charging procedure in the interests of cooling efficiency as well as electrical efficiency might be desirable.

II. EXPERIMENTAL WORK

A. Narrative

28. Experimental work has been done in the development of a system of ventilation which would take advantage of cooling through the lugs. Temperature measurements have been made on the experimental cell during the finishing rate, cycling, discharge and on stand using the method of cooling developed and the present closed-cell system for purposes of comparison. Temperature rise of the air passing through the cell, water-loss, and the effect of humidity on cooling and water-loss have been studied for the closed-cell system.

29. The cooling effect of air passing over the sides of the cell has been studied.

30. The lower limits of explosion of hydrogen in air and oxygen and various combinations of air and oxygen and the effect of glass wool on these limits have been measured. The explosion pressures of hydrogen in oxygen and the effect of glass wool on these pressures have been

measured. Many explosions have been run in a cell under various conditions of ventilation with glass wool packed in the space above the tops of the plates. In conjunction with this work the possibilities of induced flow through the cell top have been studied.

31. The effect of glass wool in cutting down acid spray has been noted during the course of the work.

B. <u>The Study and Development of Cooling Through the Lugs</u>.

1. The Set-up .

32. For this part of the work the cell (Gould OWTX-49) was set up in a room which enabled temperature control of the air. The cell was insulated by packing glass wool around the sides to a depth of four inches and enclosing the whole in a plywood box. The lead coating was removed from the lugs and one set of lugs was connected to a rectifier for charging the cell. Copper bus-bars were bolted to the remaining six lugs. These bus-bars extended from the lugs to one-half inch beyond the side of the cell, and except those to which the rectifier was attached would approximately represent one cell's share of the usual cell-to-cell connection in a battery. Cooling was achieved by setting up fans on one side of the cell which could blow air over the top of the cell along the length of the bus-bars. The temperature of the cell was followed by means of a three-junction chromel-constantan thermocouple, the junctions of which were enclosed in glass tubes inserted through the top of the cell so that the bottoms of the tubes were located in the electrolyte between the tops of the plates. Leads from this thermocouple and another multijunction thermocouple used to measure the air temperature of the room were run through the wall to a recorder in an adjacent room.

33. Three sets of bus-bars were experimented with, one plain and two finned. The finned bus-bars were constructed by silver-soldering flat copper fins to one side of each bar. The bare bus-bars gave a total of 52 square inches per lug. The finned bus-bars gave total areas of 150 and 400 square inches per lug. The finned bus-bars are referred to in this report as the "75" finned bus-bars and the "200" finned bus-bars respectively. The design of the finned bus-bars is shown in Plates 1 and 2. The bare bus-bars were the same as the "75" finned bus-bars without fins.

34. The cell was ventilated either naturally (i.e. no forced air flow) or with a small air flow (1/2 - 1CFM) through the top of the cell. If a forced air flow was used the cell top was packed with glass wool so that the cooling effect due to evaporation would be very small.

2. The Procedure.

35. The cell was heated by means of gassing at a rate slightly above the finishing rate of the cell until it came to constant temperature.

This method was used because it gave fairly fast, controllable, and uniform heating. The reactions going on in the cell were definitely known and therefore appropriate quantitative calculations of the heating and cooling effects could be made.

36. The cell was started on charge at 310 amperes at a low temperature such that it could reach 95% or better of the theoretical gassing before the cell temperature came up to 100°F. It was continued on charge with air blowing over the busses until it came to constant temperature and remained there for a period of at least four hours. The temperature was recorded during the run.

37. Forty-eight heating curves of this type were run in developing this method of cooling. The following variables were changed during the study: rate of flow of air over the top of the cell-between zero and 600 F.P.M., the temperature of the air - between 62° and 95°F., the electrolyte level - between 3 - 4 inches and 1 inch below the top of cell, and the surface area of the bus-bars attached to the lugs - between 52 and 400 square inches per lug. No variables were changed during the course of any one run. Cooling curves with the cell on stand were run under some of these conditions.

3. Data and Results.

38. The data on this part of the work is summarized in Tables I, II and III and illustrated in Plate 3 through 9. Table I gives the equilibrium temperatures of the cell with the plain bus-bars attached and shows the effect of lowering the temperature of the air passing over the bus-bars. Table II gives the equilibrium temperatures with the "75" finned bus-bars attached and shows that much more efficient cooling can be obtained by raising the electrolyte level in the cell, and (by comparison with Table I) by increasing the surface area of the bus-bars. Table III gives the equilibrium temperatures with the "200" finned bus-bars attached, largely as a function of the velocity of the air over the busses. By comparison with Table II it shows that no great increase in efficiency has been obtained by the additional increase in area of the bus-bars. The results are listed in order of decreasing equilibrium temperature in any one table to facilitate comparison. Plates 3, 4, 5, and 6 illustrate these effects. Plate 5 also shows that no great increase in cooling efficiency is obtained by raising the velocity of the air over the busses above 300 - 400 feet per minute. Plate 7 gives a complete picture of these effects, except the air velocity effect, and pictures the gradual development ofthe method of cooling until the maximum in efficiency has been approached. Plate 8 contains three cooling curves and shows that cooling on stand can take place very rapidly at high temperatures.

39. The data and the curves are largely self-explanatory and show that the equilibrium temperature is a function of the temperature and velocity of the air over the cell, the surface area of the bus-bars, and the height of the electrolyte level within the cell.

40. From a study of the data and the method used in obtaining it two important results may be derived. First, an experimental value of the specific heat of the cell can be calculated, and second, from this value and the heating curves the amount of heat which the cell is losing under the conditions imposed can be calculated. Consider the method used in heating the cell. A certain amount of electrical energy is passing into the cell. It is doing work in two ways only; it is producing gas and it is heating the cell. These can be the only two results because the cell is gassing the theoretical amount for the current input. The total amount of electrical energy input can be calculated from the equation:

$$W = EI$$

where W is the energy in watts, E the voltage of the cell, and I the current flowing. At 310 amperes with the Gould OWTX-49 gassing over 95% of the theoretical, the voltage of the cell was measured to be 2.5 volts, consequently the energy input to the cell is calculated by the above equation and the suitable conversion factor to be 667 kilograms calories per hour. At 310 amperes, under the theoretical gassing condition, the cell electrolyzes 5.8 moles of water per hour to hydrogen and oxygen gas. The energy used in this process is given by the thermochemical equation (reference (o) pg. 249):

$$H_2 \text{ (gas)} + 1/2\, O_2 \text{ (gas)} \longrightarrow H_2O \text{ (liquid)} + 68.4 \text{ kilogram}$$

calories at 68°F., which in effect states that the electrolysis of one mole of water to form hydrogen and oxygen gas at 68°F. requires 68.4 kilogram calories of energy. Therefore, 68.4 x 5.8 or 397 kilogram calories of the total input energy are going into the electrolysis of water. The remainder or 270 kilogram calories per hour must be going into heating the cell, and if the temperature rise of the completely insulated cell were known its specific heat could be calculated.

41. From Plate 3 curve 2 the temperature rise of the cell under almost adiabatic conditions is 3.17° per hour. When a correction of 0.35° for the heat loss through the insulation (which can be found from the cooling curve of the insulated cell-Plate 8, curve 2) is added the temperature rise is calculated to be 270 ÷ 3.52 or 76.8 kilogram calories per °F. From a complete breakdown of the component parts of the cell (Table VI) the specific heat of this cell can be calculated to be 81.3 kilogram calories per °F. These values just check within experimental error, and for purpose of calculation a weighted means of 80.0 kilogram calories per °F. will be used.

42. This value then enables the calculation of the amount of heat which is being lost from the cell by the heating curves, and, to a much less reliable extent at high temperatures but more reliable at low, from the cooling curves. For example, if the cell is heating at

the rate of one degree per hour and the total heat input is 270 kilogram calories per hour , then 270 minus 80 or 190 kilogram calories must be passing out of the cell each hour. At equilibrium evidently 270 kilogram calories per hour are passing out. Using this method the curves of Plate 9 were constructed from curve 6 of Plate 5 and curve 3 of Plate 8. There are two important differences in the conditions involved: first, in one case the cell is gassing and in the other it is not, and second, in the case of the gassing cell the air temperature is ten degrees higher. However, by plotting temperature differential between the cell and the air the second variable is eliminated and the curves shows that gassing greatly enhances the cooling obtainable, particularly for the smaller temperature differentials. The non-gassing curve (calculated from the cooling curve, cell standing) may be subject to a rather large error which would tend to make the heat loss higher than it should be for a given temperature differential, as will be discussed in the next section. Thus, the difference between the gassing and the non-gassing condition may amount to more than the curves indicate.

4. Discussion of Errors.

43. All measurements of the absolute values of temperature are correct to within ± 0.5°F. The recordings could be read to that precision and the recorded temperatures were frequently checked by means of a thermometer known to be correct to within ± 0.2°F. Air temperatures of the room could be maintained within ± 1° of a desired temperature once the temperature was reached. The recordings show that the maximum variation of the room temperature during the time the cell was at equilibrium was ± 1°F. Usually the cell would be started heating at the same time the room would be started cooling, consequently the early part of the heating curves were sometimes subjected to temperature variation, particularly when the runs were made at temperatures below 80°F.

44. There is some question as to whether the cell temperature measured at the tops of the plates is truly indicative of the whole temperature of the cell. It is believed that they are in the case of the gassing cell, because gassing has been found to equalize temperatures throughout the cell (references (b) and (i) by stirring up the electrolyte. This is also indicated indirectly in three ways. First, the recorded cell temperature might go down 10 - 20°F during the process of watering the cell but would be back up to within a degree or two of the original temperature within twenty minutes to an hour after watering, if the cell was gassing. Second, examination of Plate 10 shows that after the resumption of charge the heating rate is over ten degrees an hour, a much greater temperature rise than could be accounted for by the heat input to the cell, which could only be due to gassing equalizing the temperature throughout the cell. Third, and most conclusive, the specific heat of the cell calculated from the temperature rise of the insulated cell gives

a good check with that calculated for the component parts of the cell. This fact is also a good indication of the correctness of the method of calculation of the heat input to the cell.

45. From many observations the charging rate was 310 ± 10 amperes. Ordinarily the rate would start out at 320 amperes and drop back to 310 in a few hours at which it would hold during the remainder of the run. The rectifier ammeter was calibrated using a precision shunt and meter and found to be good to ± 5 amperes over the whole range.

46. The gassing rates were measured enough times during the early runs to determine that the cell would reach 95% or better of the theoretical gassing, within a few hours after a run was begun. The gassing measurements were made with a wet-test meter and a stop watch and corrected to standard temperature and pressure for purpose of calculation. The fact that the calculated gassing checked the measured within 5% was a check on the instruments and the precision is considered to be good enough for the nature of the experiment.

47. Air speeds were measured by placing an anemometer in the air stream behind the fins in eight locations on the cell top and averaging the result. The air speed behind the row of fins nearest the fans would run about 30% higher than that behind the far row. The anemometer was later checked against two new instruments, both reportedly accurate to within 3%, and was found to agree with both to within 3%. The wide variation in flow over the cell top makes the instrument error negligible. The average air speeds quoted are considered to be precise within no better than ± 10%. This precision is as good as is necessary in view of the fact that a 10% change in air speed at velocities above 300 F.P.M. or so would have a negligible effect on the equilibrium temperature as shown by Plate 5.

48. Errors in measurement of the surface area of the fins and the height of the electrolyte are negligible.

49. Examination of the data shows that check runs usually gave equilibrium temperatures within a degree of each other, while the early parts of the heating curves sometimes show discrepancies in the heating rates. Enough data has been taken so that the curves taken for illustration may be considered typical for their conditions.

50. The experimental value of the specific heat is subject to error in the current, the voltage, and the rate of heating. If the specific heat is calculated assuming maximum possible error in those measurements its value lies between 69 and 85 kilogram calories per °F. It is believed that from calculations under several conditions of cell heating the value is much more precise than that and is 77 ± 3 kilogram calories per °F.

51. Regarding Plate 9, in general the error may be quite large for the

calculated value of the heat loss, because small differences in estimating the rate of heating produce large differences in the value of the heat loss. For example an error as small as 0.2°F. per hour in estimating the heating rate results in 4% error when the heat loss in 180 kilogram calories per hour. Since the temperature cannot be read to any better than 0.5°F., then the values plotted for the gassing curve of Plate 9 may be subject to as much as 10% error. The non-gassing (cooling) curve, in addition to this error, may be subject to considerably greater error if the measured temperature is not indicative of the whole cell temperature. This is very likely to be the case, especially when there is a large temperature differential existing between the cell and the air. This is illustrated for an extreme condition in Plate 10, where evidently the recorded temperature is considerably lower than the average cell temperature, and indicates that cooling on stand especially during the first few hours may be localized to a large degree in the top of the cell. Apparently convection currents in the electrolyte are not strong enough to prevent this condition from arising in this cell, at least during the first few hours on stand. At any rate the qualitative effect would be to bring the non-gassing curve of Plate 9 even further below the gassing curve than the calculations indicate.

C. <u>Comparison of Cooling through the Lugs with Closed-Cell Ventilation.</u>

52. This work may be divided into three general parts: (a) comparison by means of heating curves which were run in the same manner or during the study of cooling through the lugs, (b) comparison by means of cycling the cell, (c) comparison by means of high rate discharges. Under (a) is also included a comparison of cooling on stand and the effect of humidity on cooling.

1. The Set-up.

(a) Heating Curves.

53. For this part of the work the Gould OWTX-49 was left in the same room as was used in the development of cooling through the lugs. It was stripped of its bus-bars and fans, and cooling was accomplished by blowing air through the regular ventilation system. The air was furnished by a high pressure line from which it came out 4 - 8% saturated. This is referred to as "dry" air in the Tables and Plates. Taps were placed in the ingoing and outgoing air tubes so that the water content and temperature of the air could be measured. The incoming air line was equipped with an instrument for measuring the volume of air flow.

54. The effect of humidity was later studied on an Exide VLA-47. The cell was set up outside the building with the same electrical connections as previously described, and the same air connections with these variations. Two saturating columns were added to the incoming air line. These

contained water, crushed tile, heating units and thermostats, so that 85 - 95% saturated air could be delivered to the cell at any temperature from 68 to 95°F. The cell case itself and the wooden box in which it was enclosed served to insulate the cell. During the course of the work it was found that this incomplete insulation might be affecting the results and the cell was insulated with glass wool as previously described. The temperature of the input dry air was regulated by passing it through a copper coil immersed in a water bath of controlled temperature.

(b) Cycling the Cell and High-Rate Discharges.

55. The Gould OWTX-49 was moved into a room where air temperature was controlled at 78 ± 2°F., and where connections could be made for cycling the cell under controlled current rates and cell voltages. The two cooling systems were employed just as described previously, except that air was sucked through the closed-cell ventilation system instead of blowing it through and no attempt was made to control or measure humidity.

2. The Procedure.

(a) Heating Curves.

56. The cell was operated under the same general procedure as described for cooling through the lugs. The air flow as adjusted to the desired flow rate and the cell allowed to charge on 310 amperes until the equilibrium temperature was reached. Ten heating curves of this type were run at flow rates of from 2 to 6 C.F.M. and between air temperatures of 75° and 95°F. This enabled a comparison with the previously obtained data under several conditions. Cooling curves were run under some of these conditions with the cell on stand.

57. Water-loss measurements were made by drawing a measured volume of air from both the incoming and outgoing ducts through glass sampling tubes by means of the taps provided. The sampling tubes contained anhydrous calcium chloride to collect the water vapor. The gain in weight of the calcium chloride tubes was determined on a chemical balance, and the weight of the water from the incoming tube subtracted from the weight of water from the outgoing tube to obtain the water-loss. The results were calculated in terms of water-loss in grams per minute and plotted against the electrolyte temperature. During the course of this work the top of the cell was filled with glass wool to a density of approximately two pounds per cubic foot and the vapor in the outgoing air stream tested for acid mist by holding a piece of wet blue litmus paper in the air stream.

58. The rise in temperature of the air passing through the cell was found by obtaining the difference between the temperature of the input

and outgoing air by means of thermometers in the air streams. The temperature rise was plotted against the electrolyte temperature.

59. In order to obtain the effect of humidity on cooling, heating curves were run on the VLA-47 in the same manner as previously described for other heating curves. The cell was ventilated at 6 C.F.M. using both dry and 85 - 95% saturated air between 75° and 90° F. Cooling curves were run under some of these conditions. The temperature and humidity of the input air was controlled, but the ambient air temperature varied with the weather. The ambient air temperature was recorded for all runs. Under the cell-insulated conditions two heating curves were run, one with dry air and one with 85% saturated air, both at 90°F.

(b) Cycling the Cell.

60. The OWTX-49 was cycled by discharging at 1200 amperes for six hours, followed immediately by a constant potential charge at 2.37 volts. Two cycles were run with closed-cell ventilation at 6 C.F.M. with the humidity uncontrolled and unmeasured. Two cycles were run with cooling through the lugs at an air speed of 470 F.P.M. over the top of the cell. The cell temperature was recorded during the cycles.

(c) High-Rate Discharges.

61. The cell was discharged at 2500 amperes, using several different starting temperatures, and at 5000 amperes using closed-cell ventilation at 6 C.F.M., and cooling through the lugs with an air speed of 645 F.P.M. over the finned bus-bars. Again for closed-cell ventilation, humidity was uncontrolled and unmeasured.

3. Data and Results.

(a) Heating Curves.

62. The results of the ten heating curves are recorded in Table IV which lists the equilibrium temperatures in decreasing order and the conditions under which they were obtained. There is not enough data to draw any overall general conclusions about this method except that the equilibrium temperature is very dependent on the volume of air flow passing through the cell. Two runs made under maximum flow conditions (6 C.F.M.) give slightly higher equilibrium temperature than the best results obtainable by means of cooling through the lugs. These points are illustrated in Plates 11 and 12. Plate 13 gives the best cooling curve, cell on stand, obtained for closed-cell ventilation and compares it with three theoretical curves. Curve 1 was calculated for 100% efficiency in heat exchange to the air. Curve 2 was calculated for 100% efficiency in cooling by evaporation. These were calculated for the same input air temperature as the experimental curve. Curve 3 is a composite of 1 and 2. A comparison of the experimental curve with

the theoretical curves brings out three points of interest. First, cooling by evaporation could be a much more effective means of cooling than heat exchange to the air, and actually must account for the largest part of the cooling effect, since cooling by the exchange to the air is incapable of producing the experimental result. Second, the recorded temperature as measured at the tops of the plates shows the cell cooling at a faster rate over the first three to four hours than is possible according to the theoretical curve. This can only mean that at least for the first three hours the cell temperature as measured at the tops of the plates is not an exact indication of the whole cell temperature and that the top of the cell is in fact cooling faster than the rest of the cell. Third, at the fourth hour the experimental curve crosses the theoretical curve and the cell cools at a rate much slower than that which is theoretically possible. This indicates that the air is passing through the cell and coming out less saturated than possible with respect to the electrolyte temperature. In other words, the efficiency of the system is far from the maximum possible. Plate 14 compares the best cooling curves obtained by both methods of cooling. They are under comparable temperature conditions but the humidity of the air for closed-cell ventilation was not recorded; it was probably between 40 and 70% relative humidity. This means that if it were dry the experimental cooling for closed-cell ventilation might have been a little faster and might have compared more favorably with those for cooling through the lugs. However it does represent a condition which would more closely approximate service conditions, than if dry air had been used. It may be concluded that cooling through the lugs is a more efficient method of cooling than cooling by means of closed-cell ventilation.

63. The curves of Plate 15 were constructed from the heating curve for 6 C.F.M. of Plate 11 and the experimental cooling curve of Plate 13. Again there is a difference of about ten degrees in the air temperature for the gassing and the non-gassing condition. In this case it is questionable whether or not plotting against the temperature differential between cell and air entirely overcomes this difficulty because cooling by this method (closed-cell ventilation) doest not depend to such a large extent on that teperature differential. For any purpose except comparison of the methods it is not worth much. However, it does indicate that gassing enhances cooling to a large degree, and if Plate 16 is referred to it indicates that gassing enhances cooling by closed-cell ventilation to a greater degree than it enhances cooling through the lugs. It is also to be noted that while in both cases (i.e. both methods of cooling) the air temperatures are not comparable for the gassing and non-gassing curves of either method, they are for the gassing curves of each method. Consequently, Plate 16 shows that while there is not much difference between the two methods for a gassing cell, there is considerable difference for a non-gassing cell, and cooling through the lugs is a better method in either case.

64. Plate 17 shows the plot of water-loss versus electrolyte temperature at 2 and 6 C.F.M. with the cell gassing and on stand. These are curves 1, 2, 3, and 4. They show that the water-loss is not greatly increased by stepping up the air flow from 2 to 6 C.F.M. for a non-gassing cell, but is greatly increased for a gassing cell. This would indicate that not much better cooling could be obtained by increasing the air flow above 2 C.F.M. except when the cell is gassing. Curve 5 shows the effect of 50% saturation of the incoming air on the water-loss at 2 C.F.M. for the gassing cell. Obviously humidity plays an important part in water-loss and cooling. Curve 6 shows that glass wool in the cell top decreases the water-loss to a very great extent. During this part of the work the effectiveness of glass wool as a trap for acid mist was tested by placing a strip of wet litmus paper perpendicular to the outgoing air stream from the gassing cell in which the void space above the electrolyte was packed with two pounds per cubic foot of glass wool. For intervals up to one hour no indication of acid in the air stream could be found. The liquid drops at the top of the glass wool were also tested with litmus paper and found to contain no acid.

65. Plate 16 gives the gain in temperature of 88°F. air passing through the cell as a function of the electrolyte temperature. There is not much difference for the cell in any condition, but the faster it passes through the smaller is the temperature differential. At 130°F. cell temperature and 6 C.F.M. with the cell gassing, the heat lost to the air would be 4.5 x 15 x 60 x 6 or 24.2 kilogram calories per hour, which shows definitely that the amount of heat lost to the air even for a hot cell and fast air flows is but a small quantity. This amount of heat loss would achieve a cooling effect on the cell of 0.3°F. per hour.

66. The cell heating curves showing the effect of humidity are given on Plate 19. Curves 3 and 4, which were run without insulation of the cell and the low input air temperature of 70°, show a 5° higher equilibrium temperature for the 95% saturated air in spite of the fact that the ambient temperature was 5° higher for the dry air run. In the case of the insulated cell the equilibrium temperature was also 5° higher for the saturated air. The curves show that humidity plays an important part in the amount of heat which can be lost from the cell by evaporation. The point in determining the humidity effect is this: most of the emphasis in the experimental work has been on the heating curves, but the work on closed-cell ventilation compares more favorably with the system of cooling through the lugs on the basis of the experimental work than it would in service. The humidity effect shows that the comparison is even more favorable to cooling through the lugs than the experimental work had indicated.

67. Plate 20 shows two cooling curves obtained on the uninsulated cell, one for saturated input air, the other for dry input air, both at very

closely the same ambient temperatures. The effect of humidity on the cooling is very marked, even for a comparatively high temperature differential between the cell and the air.

68. Thus the overall results of this comparison show that cooling through the lugs is more efficient than cooling by means of closed-cell ventilation even when dry air is used in the closed-cell system. The work shows the comparison to be even more favorable when the effect of humidity is considered.

(b) Cycling the Cell.

69. Plate 21 compares the two methods under cycling conditions. Each curve represents two cycles under the conditions concerned. It shows that although the cell starts out at a higher temperature (3°) in the case of cooling through the lugs, it ends up the cycle about 5° lower than in the case of closed-cell ventilation. It must be pointed out that this work was done in a room at 78°F. which makes the comparison more favorable to cooling through the lugs than would be the case at a higher room temperature due to the sensitivity of the lug method to temperature differential between air and cell. However, the basis of the heating curves run previously, no worse than an even break would be expected, even at room temperature as high as 90°F.

(c) High-Rate Discharges.

70. Plate 22 shows that for high-rate discharges of about 2500 amperes, cooling through the lugs may be a shade more efficient than closed-cell ventilation, but both are definitely better than no ventilation at all. At 5000 amperes the results are compared in the accompanying Table.

Table A

Cooling at a Discharge Rate of 5000 Amperes.

#	Cooling Condition	Initial Temp. °F.	Final Temp. °F.	Time (min)	Temp. Rise in % min.
1	6 CFM through cell	109	135	35	.80
2	6 CFM through cell	120	148	35	.80
3	645 FPM over "200" fins	118	139	28	.75
4	645 FPM over "200" fins	118	141	31	.74
5	No cooling	102	125	29	.79

71. The table shows that for discharge rates as high as the one-hour rate (5000 amperes) there is no appreciable difference between the two systems. However, during high-rate discharges the cell might be expected to reach rather high temperatures and as has been shown previously, cooling

[redacted]

after such discharges will be accomplished more effectively by cooling through the lugs, than by closed-cell ventilation.

72. There is evidence to show that at these high discharge rates heating takes place to a greater extent at the top of the cell than lower down in the cell. The resistance of the CWTX-49 on which these tests were run has been measured at three different discharge rates by means of an oscillograph. It was found to be $0.84 \times 10^{-4} \pm 1\%$ ohms. Using this figure and that calculated for the specific heat it can be calculated from the equation:

$$W = I^2 R,$$

that discharges at 2500 amperes and 5000 amperes should heat the whole cell at 6.1°F. per hour and 0.4°F. per minute respectively, assuming no other heating effect than that due to the electrical resistance of the cell. The chemical reaction taking place in the cell on discharge is an endothermic reaction and thus would contribute some cooling effect, so the assumption is pretty safe. Experimentally, it is found that even with a cooling effect taking place, the temperature measured at the top of the cell at the 2500 ampere discharge rate rises 17° the first hour and 7° the second hour, while at the 5000 ampere rate the average heating over the whole time of discharge is 0.79° per minute. This is a clear indication that the cell is heating faster at the top than at the bottom, and probably arises from unequal current distribution within the cell. From a cooling standpoint this is probably more favorable than otherwise for the present cell design, because it concentrates the heat near the place where the cooling is taking place, i.e. at the top of the cell.

4. Discussion of Errors.

(a) Cell Heating Curves.

73. In general the errors accompanying this part of the work are the same as those for cooling through the lugs for comparable measurements. Again it is questionable whether or not the cell temperature as measured at the tops of the plates is indicative of the whole cell, and the same discussion given previously for cooling through the lugs applies here, except that in addition it is believed that cooling due to evaporation keeps the equilibrium temperature as measured at the top of the cell about 2° to 3° lower than the whole cell. This is indicated by the fact that if the cooling air is turned off the temperature quickly (within ten minutes) jumps up two or three degrees. This would mean that while heating curves are correct as far as rates are concerned, the equilibrium temperatures might actually be 2 - 3°F. higher than the value stated. This same effect has been noticed in a previous work (reference (j)). No such effect was noticeable in the case of

cooling through the lugs, and this is another point in favor of the lug method in the comparison of the two.

74. The value of the volume of flow was measured by means of an Enco Flow Meter (550 CFH range) which was calibrated against a meter prover up to 3 C.F.M. The scale was found to be correct to ± 5%. The calibration check could not be made above 3 C.F.M. but because of the good check below that value, it was assumed that the error in the instrument above that value was insignificant compared to the error introduced by the method. The flow rate fluctuated as much as ± 1/2 C.F.M. at 6 C.F.M. due to variation in line pressure, thus the volume of flow is only accurate to ± 10% of the value quoted.

75. It is believed that the measurement of the absolute value of the water-loss as illustrated in Plate 17 for the gassing condition is subject to rather large negative error. These curves are evidently considerably low because the total cooling at equilibrium which can be calculated from them is lower than the specific heat indicates it must be, and the water-loss as measured by the amount necessary to bringing up the water level to a reference mark is greater than can be calculated by means of these curves. This result is probably explainable when the method of measurement is considered. The tap was inserted in the outgoing air stream with its open end pointing away from the air stream and not into it. Thus heavy particles of condensate traveling by the tap at high velocity would not be able to be sampled, while true water vapor of course would enter the tap. The sample therefore might take into account the water passing out as true vapor but not that passing out as mist or condensate. It is estimated that the maximum error in the points on the curves for the non-gaining condition are correct to within ± 5% of the values given.

76. The error in measurement of the temperature differential between the incoming and outgoing air is negligible and made more so because this is a relatively unimportant cooling effect.

77. The most important source of error in the results of the study of the humidity effect is the variation of the ambient temperature in the comparison of curves 3 and 4 of Plate 19. The input air was controlled to ± 2°F. in all cases. The relative humidities given are ± 5%. These errors are immaterial because the maximum difference in the equilibrium temperatures for practically complete saturation of theair is only 5°F. as indicated by curves 1 and 2 of Plate 19. This difference will vary with conditions of cell temperature and input air temperature, however, only a qualitative effect was desired, particularly at high input air temperatures (90°F.) and it is considered that such has been obtained. All the data which has been collected for high humidity indicates that high humidities will reduce the efficiency of cooling by the closed cell system. Humidity has practically no effect on cooling through the lugs.

through the lugs.

(b) Cycling the Cell and High Rate Discharges.

78. The absolute errors in the values measured in these studies have little significance because a comparison is involved and error in measuring the amperage and voltage should affect either method the same amount in the same way. Errors in air velocity and volume flow, and in temperature measurement are the same as have been quoted previously. The most significant error was due to the fact that the method of control during cycling did not allow the current to come down to exactly 310 amperes at the end of a charge. This would be important because of the quantity of heat involved during the gassing phase. The error was eliminated by repeating the cycles until runs were obtained which gave a final amperage of 300 - 320 at the end of the charge.

D. <u>Cooling Through the Sides.</u>

79. This method has been considered separately from the others because it could be used to supplement either one of them.

1. The Set-up and Procedure.

80. The Exide VLA-47 was insulated completely with glass wool and set up for charging with gassing at 310 amperes, just as was done in the previous experimental work. One heating curve was run on the insulated cell after which the insulation was removed and the cell enclosed in a box so that air at a constant temperature varying between 85° and 90°F. could be blown up and around the cell at a velocity of 30 F.P.M. One heating curve was run with the cell in this condition, then the box was removed and another heating curve was run with fans playing air over the sides at an average velocity of about 200 F.P.M. and at the ambient air temperature. One cooling curve was run with the cell in a room at constant temperature and air passing over the sides at a velocity of about 10 - 30 F.P.M.

2. The Data and Results.

81. The heating curves are shown in Plate 23 and it can be seen that the equilibrium temperature of the gassing cell with low velocity air over the sides is about 30 - 35° higher than the ambient air temperature (Curve 2). The Curve (1) for the insulated cell is given for comparison. This temperature differential is a little higher than the temperature difference existing for the cell and the air in the case of cooling through the lugs for comparable temperatures. From Curve (2) of Plate 23 and the cooling curve of Plate 24 the curves of Plate 25 were constructed by the same method as was used previously for curves of this nature. The value of the heat capacity of the Exide VLA-47 cell which

is necessary for the construction of the curves of Plate 25 was experimentally obtained in the same way as was done for the Gould OWTX-49 and was found to be 90 ± 3 kilogram calories on the basis of three determinations. Table VII gives a breakdown of the VLA-47 construction and the value of the heat capacity calculated therefrom. This value, 88 kilogram calories per °F. was used in the construction of the curves. Again it is evident from Plate 25 that gassing has a large effect on the ability of the cell to lose heat. The heat loss through the sides is compared with the heat loss through the lugs (Plate 9) in Plate 26. It is evident that cooling through the lugs is more efficient above a temperature differential of about 26°F. Below this the method of cooling though the sides is more efficient, especially when the cell is not gassing.

3. Discussion of Errors.

82. There are no new measurements in this part of the work except the rate of flow over the side of the cell which is subject to considerable variation for the high speed (200 F.P.M.) due to non-uniformity of flow over the surface. Two fans were placed at opposite corners of the cell at the bottom and the flow directed up around the sides. The air speeds were higher near the fans and considerably lower nearer the top of the cell. No attempt has been made to study cooling versus the rate of flow over the sides because it was desired only to get some idea of the comparative cooling which could be obtained by this method. The data which has been collected for this part of the work is sparse but it is good and offers a good comparison of the heat loss which can be achieved by this method for the Exide VLA-47.

E. Explosion Hazards

83. The work on this phase of the problem may be divided into the following sections:

(a) the lower limits of combustion of hydrogen in air, oxygen and air-oxygen mixtures in various densities of glass wool.

(b) explosion pressures of hydrogen in oxygen and in oxygen with glass wool present, and

(c) explosions in the cell itself with two methods of ventilation - glass wool in the cell.

1. The Set-up.

(a) Lower Limits of Combustion - the Effect of Glass Wool.

84. The limits of combustion were run in small cyclindrical steel bomb

having a total volume of 580 cc. The bomb was fitted with valves to allow the gasses to pass in and out, a spark-plug for firing the gasses, and a valve to which a mercury manometer could be attached. The outgoing gas line was led through a drying tube, a thermal conductivity cell calibrated to give the percentage of hydrogen in the air, and finally through a Pauling Oxygen meter. Various oxygen meters were used, the range depending on the concentration of hydrogen being studied. All were calibrated before use. The bomb was constructed so that one end could be screwed off for putting in the glass wool.

(b) Explosion Pressures - The Effect of Glass Wool.

85. For measuring explosion pressures a much larger, long cylindrical steel bomb having a volume of 7.61 liters was used. In addition to the fittings previously described for the small bomb, this one contained a piezoelectric crystal at one end, leads from which ran to a cathode ray oscilloscope. Thus a signal to the oscilloscope from the crystal distorted by an explosion would cause a deflection in the trace on the screen of the oscilloscope, the deflection being proportional to the pressure produced by the explosion. By means of adjustments on the control panel of the oscilloscope maximum height of the deflection could be made to correspond to any given pressure up to 180 lbs. per sq. in., thus giving ranges of various sensitivity for measuring weak and strong explosions to an accuracy of about 10% in general. In this set-up the spark-plug was replaced with a hot wire for igniting the mixtures, because the radiations from the spark were picked up by the oscilloscope and affected the trace produced by the explosion.

(c) Explosions in the Cell.

86. For this work the cell (OWTX-49) was set up for ventilation in two ways. First the filling vent tube was removed and a 1/4" flat vinylite plate sealed into the central hole. A spark-plug was screwed into this plate for sparking off the gas in the cell. Four two inch circular holes were cut in the cell top about five inches each way from the sides at the corners. Fans were placed so that air could be blown over the top of the cell. Funnels of the design shown in Plate 29 were set over the holes nearest the fans for inducing a flow down and through the cell. The other two holes on the side away from the fans were equipped with elbows of 2" pipe with the mouths facing away from the direction of air flow. By this means, together with varying the current passing through the cell, any desired concentration of hydrogen could be obtained in the cell. The concentration was determined by the thermal conductivity cell and the Pauling Oxygen meter from the center of the top of the cell or in one of the outlet elbows. The void space above the plates of the cell (partially filled with electrolyte) was packed to a density of about 4 lbs. per cu. ft. of glass wool. The second method of ventilation consisted of completely sealed cell except for a 1/8" hole to allow the escape of the gases.

87. In connection with the first ventilation method described, experiments were performed on a simulated cell top in the laboratory which would show what kind of an induced flows could be expected to be obtained using glass wool of various pack densities in the cell top. For this work a box having the same general shape and dimensions as a cell top above the electrolyte level, but without the shoulders in it, was constructed and fitted with funnels as described for the actual cell. Fans were set up to blow air over the simulated cell top and instead of using elbows in the outgoing air stream, two holes were drilled into the side of the box where calibrated flow meters of the thermal conductivity type used to measure the flow in an individual submarine cell were inserted. These enabled the volume flow through the cell top to be measured as a function of the air speed over the top of the cell and the pack density of the glass wool placed inside the box.

2. The Procedure.

(a) Lower Limits of Combustion - The Effect of Glass Wool.

88. The gases were mixed in a tube before entering the bomb and were passed through the bomb until the measuring instruments indicated a constant mixture in the bomb. It was then sealed by closing the valves and the gas mixture sparked off. Combustion was determined by opening the bomb to the manometer and noting the presence or absence of a vacuum. This procedure was followed for a series of mixtures of increasing hydrogen concentration up to and beyond the concentration at which combustion would take place. The highest concentration which did not explode was considered to be the lower limit of explosion under the conditions imposed. Check runs were run by changing the pack of glass wool.

(b) Explosion Pressures - The Effect of Glass Wool.

89. Explosion pressures were determined by touching off a mixture of the gas and observing the deflection produced in the oscilloscope trace. The ranges of pressure used on the oscilloscope were calibrated by filling the bomb with compressed air or nitrogen to a known pressure and suddenly admitting it into a small chamber containing the piezo-electric crystal by means of a quick-opening high capacity valve and observing the resultant deflection of the oscilloscope trace. The gas mixtures were exploded by a hot wire, the explosion producing a deflection in the oscilloscope trace. The height of the deflection was noted and the pressure found from the calibration curve of the range in use. In this way the explosion pressures developed by mixtures of hydrogen and oxygen and those mixtures in the bomb with a 4 lbs. per cu. ft. and 5 lbs per cu. ft. pack density of glass wool were measured.

(c) Explosions in the Cell.

90. To determine the effect of explosions in a cell ventilated with air and packed with glass wool, the cell was brought to maximum gassing. The fans were turned on and the air speed over the cell top adjusted so that the lowest concentration of hydrogen possible was obtained in the cell. The mixture present was then sparked off with the cell still gassing and being ventilated. The gassing rate was adjusted to correspond to the amount which would be produced by a cell gassing the theoretical rate at 300 amperes. This cell (OWTX-49) produced 68% hydrogen and 32% oxygen. A series of explosions were run on mixtures of increasing hydrogen concentration produced by slowing down the air speed over the cell top. After the electrolytic mixture was reached using the induced ventilation method, without any apparent deleterious effects on the cell, the cell was completely sealed except for a 1/8" hole and further explosions were run with the cell in this condition with both the high and the normal level electrolyte.

91. The laboratory work on induced flow in a simulated cell top was done in the following way. The fans for blowing air across the top of the cell were turned on and the air speed over the top measured using th average of eight readings at various places on the cell top. The volume of the air passing through the cell was found by adding the separate volumes indicated by the two flow meters. This process was repeated for various air speeds over the top of the cell and with various pack densities of glass wool inside the box, and with two designs of funnels.

3. Data and Results.

(a) Lower Limits of Explosion - The Effect of Glass Wool.

92. A summary of the data obtained in this phase of the problem is presented in Table V and illustrated in Plate 27. In the table, the limiting concentration of hydrogen in air, oxygen and air-oxygen mixtures is given. The air-oxygen mixtures were made up to correspond to that concentration of hydrogen and oxygen which would be present in gassing a cell being swept out by various quantities of air, i.e. various rates of induced flow. The limiting concentrations are presented as a function of the pack density of glass wool. Any single trial represents a mean of at least two runs on the same pack, while different trials represent a repack of the glass wool to the same pack density. This data shows that the glass wool will prevent the combustion of any concentration of hydrogen in air for a pack density at some point between 2.5 and 5.0 lbs. per cu. ft. The exact pack density necessary to prevent explosions of hydrogen-air mixtures has not been determined in this work. Reference (k) places it between 2 and 3 lbs. per cu. ft. Glass wool raises the inflammable limit of hydrogen in oxygen only slightly - to 11% at a pack

density of about 10 lbs. per cu. ft. The highest pack density raises the limit to 49% hydrogen in the mixture representing a gassing cell being swept out by air. 49% hydrogen means 24.5% oxygen and 26.5% air. For a cell gassing the theoretical on 300 amperes (2.09 lieters per minute of hydrogen) this would represent a ventilation rate of 1.13 liters per minute of air. Thus the data indicates that if a cell packed with glass wool to a density of 9.9 lbs. per cu. ft. and gassing the theoretical on 300 amperes, could be ventilated with 1.13 liters per minute of air, no explosion could take place. These results are illustrated by the curves in Plate 27, where any point in the area under the curves represents a mixture of gasses which will not explode for the pack density of glass wool present.

93. The upper inflammable limits were not investigated, however it was evident that the upper limit is being lowered as well as the lower limit being raised, because no combustion was obtained at 72% for the 7.4 lbs. per cu. ft. pack and none at 67% for the 9.9 lbs. per cu. ft. pack for hydrogen in oxygen.

(b) Explosion Pressure - The Effect of Glass Wool.

94. The results of this work are shown entirely in Plate 28. Curve 1 represents the pressures generated by explosions of hydrogen in oxygen in the empty bomb, and shows that they may reach over 180 lbs. per sq. in. between about 26 and 81%. Curve 2 shows the pressures obtained from explosions of hydrogen in oxygen in the bomb packed with glass wool to a density of 4 lbs. per cu. ft. After about the first six explosions evidently the glass wool began to be packed into one end of the bomb because the explosion pressures jumped rather suddenly from 20 lbs. per sq. in. or less to around 40 lbs. per sq. in. When the head was removed from the bomb there was a void at the top amounting to about 1/3 the total volume of the bomb. The curve is offered to show that even with such a large void in the glass wool the pressures are still tremendously reduced. The cell was repacked to 5 lbs. per cu. ft. with glass wool and six more explosions run at concentrations near the electrolytic mixture. These showed pressures of from 2 to 8 lbs. per sq. in. Thus the data shows that glass wool in pack densities of 4 - 5 lbs. per cu. ft. can cut down the explosion pressures of hydrogen in oxygen to almost nothing.

(c) Explosions in the Cell.

95. In the first condition, i.e., the cell packed with 4 lbs. per cu. ft. of glass wool and with induced ventilation, 25 attempts were made to explode the gas in the cell, the concentrations of hydrogen ranging between 10 - 68%. Seven of these were successful and the data indicated that the lower limit of explosion would be about 30%. Then twelve explosions were run on the electrolytic mixture in the cell, all of

which did explode. Then another series of 22 explosions were run, eight of these were concentrations from 10 to 20% and fourteen were the electrolytic mixture. All of these exploded, indicating that for some reason the limit of explosion had dropped down to about 10%. Many of these explosions were delayed, i.e., after the spark was made the explosion would take place sometimes as much as five minutes later, indicating that the mixture may be slowly burning somewhere in the cell top. In two cases the explosions were allowed to continue for an hour by shutting down the fans and thus preventing ventilation. During this time a series of explosions of small but varying intensity took place every few minutes. The explosions were stopped by turning the fans and ventilating the cell again. In none of these explosions was any apparent harm done to the cell. However, the cell did become about 20°F. hotter indicating that continued explosions might cause fire. The electrolyte was raised to one inch below the cell top and a series of fourteen explosions on electrolytic mixtures were run with the funnels in place but no ventilation. In this case the explosions would delay for a few seconds and then take place with a vicious noise, apparently in the ventilators. Presumably the spark would fire the mixture which would burn quietly through the glass wool until it reached the free gas in the ventilators, then go off with a nasty bang. This was apparently harmless to the cell but the sound, if one were taken by surprise, would be enough to disturb one's composure.

97. These experiments lead to the idea of closing up the cell entirely. This was done leaving a 1/8" hole for the gases to escape. Another hole 1/2" in diameter was left loosely stoppered to enable some judgement to be made of the effectiveness of the explosions. Twenty explosions were run with the cell in this sealed condition employing electrolytic mixtures, fourteen with the normal level electrolyte and six with the high level. The explosions were very quiet and showed no tendency to repeat without benefit of the spark. In no case was the stopper in the 1/2" hole unseated, indicating that the force of the explosion was very small. At the end of this time the cell top was taken off and the glass wool examined. No voids appeared in the glass wool and no signs of sintering or general deterioration were evident.

98. In all, the gases were exploded in the cell seventy-five times without any apparent harmful effects to the cell. The work shows that the cell can be safely sealed up, except for a small vent hole, if glass wool is packed in the void space above the electrolyte to a density of 4 lbs. per cu. ft.

99. Again during the course of this work an attempt was made to detect the presence of acid spray at the mouth of the outgoing ventilation elbows. It was done in the same way as was tried before, i.e., by placing wet blue litmus paper across the outgoing air stream. No evidence of any acid mist or spray could detected, showing that the glass wool is acting as a

very efficient spray trap.

100. The results of the work as performed in the laboratory on a simulated cell top are illustrated in Plate 30, which gives the induced ventilation through the cell top as a function of the air velocity over the top of the cell and the pack density of the glass wool in the cell top. While the work was done with two different funnel designs, one the design illustrated in Plate 29 and another smaller funnel not illustrated, only one set of data is presented because there was very little difference in performance between the two. The plate shows that as the glass wool becomes more densely packed, the flow which can be induced through the cell top becomes smaller for a constant air speed over the top, as would be expected. This work taken in conjunction with that illustrated in curve 2 of Plate 27 shows that open-cell ventilation using an induced flow through the cell top is feasible, and indicates that ventilation rates could be obtained which would eliminate the possibility of explosions in the cell. For example, curve 3 of Plate 30 shows that for a 2 lbs. per cu. ft. pack density of glass wool, 28.3 liters per minute (1 C.F.M.) could be induced through the cell top for an air flow of 300 FPM over the top of the cell. For the cell gassing on 300 amperes (2.1 liters per minute of hydrogen) this induced flow would be sufficient to keep the concentration of hydrogen at 7.5%, which would be perfectly safe, as indicated by curve 2 of Plate 27. However, in view of the favorable results which have been obtained as a result of the experimental work on explosions pressures in the sealed cell, it is believed that little consideration should be given to any method of induced ventilation, in view of the benefits which can be obtained from a sealed cell. This data is only presented to show that such a method is possible, and because it was incidental in the experimental work leading to the sealed cell method of ventilation.

101. All this work involved the measurement of hydrogen concentration. The thermal conductivity set-up for measuring the concentration was calibrated by mixing the gases metered through wet test meters and dried before entering the cell. The wet test meters were checked against each other beforehand, thus this method of calibration introduces only the error in reading the wet test meters. This source of error is small compared to the reading error of the instrument for the ranges involved in these measurements. The estimated accuracy of the absolute values of hydrogen concentration is ± 1/2% in the range 0 - 25% and about ± 1 1/2% in the range of 25 - 70 %. The hydrogen concentration could also be determined by the concentration of oxygen as indicated by the Pauling Oxygen meters, which gave results which were precise to ± 1/2% in the ranges 0 - 25% and 70 - 100%, but much less precise in the in-between range. Usually the two instruments would check within a percent but sometimes they would vary by as much as 2%. The overall accuracy of the quoted values of hydrogen concentration is regarded as being no better than ± 1% absolute.

102. The explosion pressures are estimated to be accurate to within ± 10 lbs. per sq. in. in the range above 50 lbs. per sq. in. Below this they are good to ± 5 lbs. per sq. in. Thus there may be considerable error in the absolute values of explosions resulting in pressures below 20 lbs. per sq. in., however, the value of the glass wool in decreasing the explosion pressure to very low values is beyond question; the pressures of hydrogen-oxygen explosions were reduced to less than 10 lbs. per sq. in.

103. The limits of explosion in the cell itself cannot be quoted with any degree of reliability. The work shows that with a 4 lbs. per cu. ft. pack density of glass wool in the cell top, any concentration above 10% is liable to explode. However, in view of the fact that it has been shown that these explosions in the cell can be rendered harmless it is not believed that it is necessary to know these limits. It is improbable that an explosion would originate in the cell anyway.

III. DISCUSSION OF DATA AND RESULTS.

A. The Study and Development of Cooling through the Lugs.

104. There are two things of primary importance which this work indicates. First, while the method which was selected to develop this system enabled a quantitative treatment of some aspects of the work to be made, care must be exercised in the interpretation of the results. The work shows that under all cooling conditions much more heat may be drawn from the gassing cell than the non-gassing cell, which is no doubt due to the stirring action accompanying gassing. But under ordinary conditions of use a cell will be gassed only a small fraction of the time it is in use, consequently the amount of heat which can be drawn from the cell during the gassing phase cannot be used as a quantitative measure of the cooling achievable under service conditions. Second, if no change in the design of the cell is assumed, then this part of the work indicates that a close approach to the maximum possible cooling efficiency by this method has been made. The electrolyte has been raised just about as far as possible; the area of the bus-bars has been increased until further increase will give little additional efficiency and, increasing the air speed over the cell has been shown to have but a small effect beyond a certain limit.

105. Other conclusions which follow as a result of this work may be stated as below;

1. In order to take greatest advantage of cooling by this method, the air must be cooled as low as possible before passing over the battery because the heat loss is dependent to a large degree on the temperature differential between the cell and the ventilating air.

It has been estimated (reference (b)) that 25% of the total tonnage of the air-conditioning system goes into dehumidification of the submarine atmosphere. Unquestionably much of this water in the air comes from the batteries, and if it could be eliminated by changing over to another cooling system such as that which would employ air to cool through the lugs, then this tonnage might be used to precool the air passing over the cells.

2. Raising the electrolyte level in the cell would be an important factor in cooling through the lugs. An additional benefit of raising the electrolyte level would be the resultant increase in the electrical capacity of the cell due to the extra electrolyte.

3. Cooling by this method, except during the gassing phase, does not cool the cell uniformly, but cools it at the top faster than any place else in the cell, especially during the early hours after a charge.

4. Heat transfer in the cell is much less efficient for a quiet cell than a gassing cell.

B. <u>Comparison of Cooling through the Lugs with Closed-cell Ventilation</u>.

106. The work which has been done in making this comparison shows that a method of cooling has been developed which compares favorably with the cooling which can be achieved by the present system of ventilation. This is true up to air temperatures of 90 - 95°F., but no higher, because of the dependence on the lug-bus system on the air temperature, while the closed-cell ventilation system is relatively independent of the air temperature since it depends for cooling primarily on evaporation of the electrolyte. The greatest emphasis in the experimental work has been placed on a phase of the problem, i.e., the gassing phase, which least deserves it but which enabled a quantitative treatment of the problem. This allows a determination of the maximum amount of heat which can be drawn from the cell under service conditions for any of the methods considered but does not tell us the cooling which will be achieved under service conditions, because except for the short gassing phase, conditions for maximum cooling will never be approached. This report has shown only that a system has been developed which should compare favorably with the present system of ventilation under service conditions.

107. The method which has been developed is however subject to the limitations that provision must be made for enough air to carry off the heat and it must be given a high enough velocity over the cell tops to do it with good efficiency. All the heat energy which in the present system goes into the evaporation of water would, in the proposed system, have to be taken up by the air passing over the cells. But, since air does not have a very great heat capacity, it might be expected that considerably more air would have to be supplied to the batteries than

is supplied at present, and the blowers which are installed now might not be able to handle the volume necessary in case of a change over. An estimate of the amount of air necessary can be made on the basis of the heat capacities of the cell and their average temperature fluctuation. Suppose during the course of 24 hours the battery temperature fluctuated between 130° and 115°F., up and down once. Then in order to cool the battery (composed of 126 OWTX-49 cells) from 130° to 115° the total quantity of heat lost would have been 15 x 80 x 126 or 151,000 kilogram calories. If it can reasonably be assumed that the cell loses about the same amount of heat while getting up to maximum temperature as it does in reaching mimimum temperature then the total heat lost over the 24 hour period would be 302,000 kilogram calories. During this time (based on 6 CFM per cell) the blowers could have supplied 6 x 60 x 24 or 1,090,000 cubic feet of air having a total heat capacity of 4910 kilogram calories per degree F. Thus the temperature differential between the incoming and outgoing air would have had to be 62°F. To fit this picture into the story it means that at least double the supply of air is necessary than is supplied at present, assuming the maximum capacity of the blowers can supply 120 cells with 6 C.F.M. and that the exchange to the air is 100% efficient. Some of the extra air necessary might be made up by the decreased resistance to air flow resulting from the removal of the duct system.

108. Because the experimental emphasis has been on the gassing phase of the charge the work tends to show up the closed-cell system better by comparison because gassing enhances the cooling effect of evaporation to a greater degree than it does cooling through the lugs. Also, most of the comparison work was done with dry air for closed-cell ventilation. In service, the relative humidity of the air will probably run between 40 and 70% or higher. This factor must be considered in making the comparison because it has been shown that high humidity definitely decreases the cooling efficiency in closed-cell ventilation.

109. The work shows that the greatest factor in cooling under the present system can only be due to the evaporation of water. It shows that it is possible to achieve the same or better cooling by means which could make water-loss due to evaporation unnecessary, and thus largely eliminate the time and labor consuming job of watering the cells. It would help to relieve the discomfort due to high humidity, but might result in discomfort due to higher air temperatures in the ship, although possibly a good deal of this heat could be transferred through the hull to the sea water. In cold climates it could be used as a means of warming the ship's air.

C. Cooling Through the Sides.

110. The data which has been presented on this phase of the problem indicates that even without any changes in design of the cell, cooling through the sides might be used to good advantage to supplement cooling

through the lugs, at least for the VLA-47 type cell on which this work was done. As in the other methods of cooling, gassing facilitates this method a great deal. For small temperature differentials this method of cooling, on the basis of the data collected, would be a more efficient means of cooling than the other two. Presumably this method would also be accomplished with air, and would present a problem in getting enough air supplied to the cells, just as in cooling through the lugs.

111. In this connection it is noted that the German submarines (reference (d)), as well as the French previously referred to in this report apparently utilize cooling through the sides of the cell to good advantage. In addition, the German submarines pre-cool the air before it enters the battery compartment, a factor which, as has been shown, would add measureably to the cooling effect on the cell.

112. There is no good data at hand for the OWTX-49 cooling through the sides. The data which is at hand indicates that in spite of both cells having practically the same cell case the OWTX-49 cools more slowly through the sides than the VLA-47. If this is true it might be due to the inhibition of circulation of the electrolyte because of the glass mat construction around the positive plate, while in the VLA-47 circulation would be relatively free because of the "Ironclad" construction of the positive plate. The new construction of the cell case, with the ribs on the inside instead of the outside, should help to facilitate circulation of the electrolyte due to the additional free space.

D. Explosion Hazards.

113. If the present system of ventilation were to be changed over to a system taking advantage of cooling through the lugs, then the following general methods of ventilation would be possible: (1) some sort of forced draft system through the cell, with or without glass wool, (2) some method of inducing the ventilating air which would be flowing over the cell tops to flow through the cell, and, (3) allowing the cell to ventilate naturally into the air stream above it. The first of these is what the investigation aims at getting away from because of its many drawbacks. The second would be possible and safe, but it might make the danger of spillage greater and would not be as simple as the third. The third method would be extremely simple and would enable a minimum water-loss and no spillage even with a high level electrolyte. Perhaps a non-spill feature could be incorporated into the cell top. The work of this report shows that the method would be safe; it does not show that explosions in a cell can be entirely eliminated, but it does show that an explosion in the cell could be rendered harmless, by packing the air space in the top of the cell with 4 - 5 lbs. per cu. ft. of glass wool. In addition, the work indicates that acid mist or spray as a result of gassing could be eliminated 100% by the use of glass wool in the cell top.

E. General Discussion.

114. Because the work on explosion hazards resulted so favorably, and

because cooling which can be achieved by the present closed-cell system of ventilation, the whole work appears to enable a very simple method of ventilation; one which should do much to eliminate most of the drawback connected with the present system. It appears that the change-over from the closed-cell system to the proposed method would be easy to effect. The duct system would be removed from the batteries and the void space inside the cell top packed with glass wool; the cell top would then be completely sealed except for a small hole to allow the cell gases to escape and take care of breathing. The electrolyte level would be raised so that the gassing level was about one inch below the top of the cell. The lead plating would be removed from the lugs where they contact the bus-bars; fins would be soldered to the bus-bars. The present blower system would have to be adapted to the new ventilation system - which might require additional blowers, and the system would have to be arranged to allow a great enough speed over the tops of the cells. Any pre-cooling which could be given to the air would be desireable.

115. It must be remembered that all this work has been done on two experimental cells in the laboratory without benefit of a great deal of knowledge of actual conditions existing in service. The steps outlined above would be all that would be necessary for a trial installation of the proposed method. If the trial installation should prove satisfactory then additional consideration could be given to the finer points, and to points which may have failed to receive consideration in this report.

F. <u>Changes in Design and Operating Methods</u>.

116. If a trial installation of the proposed system should prove to be better by comparison than the closed-cell system, then further experimental work and consideration of changes in design which are outside of the scope of this work should be contemplated. There are some things which obviously could be done to improve cooling of the cells; however, whether or not they would be worth while would require further investigation.

117. Consider the equation for the transmission of heat through a uniform body:

$$q = \frac{k\,A\Delta t}{l},$$

in connection with cooling through the lugs. k is the heat transfer coefficient; because of the nature of the lead-acid cell any great change in k may not be possible, but it might be effectively improved. The heat takes two paths from the interior of the cell up through the lugs and out. It can either be conducted up through the electrolyte to the top where it will be transferred through the shoulders to the lugs

and busses, or it can travel up the lead grids to the copper shoulder and out through the lugs. In the first case, fins from the shoulders could be extended vertically into what is now the void space above the plates. These could be made of lead-coated copper. This would increase the area the electrolyte would come in contact with and thus effectively increase Δt, the temperature differential, by making the shoulder hotter. Such a change in design would probably be of great effect only during the gassing phase of the charge. The thickness of the lead coat on the shoulders and fins should be made as small as possible and still be consistent with the degree of protection necessary during the life of the cell. In the second case, to improve the heat transfer up the grid structure, the grids could be made of lead-coated copper. Lead has a heat conductivity coefficient which is one-tenth as great as copper, which rates as one of the best metals. This should also increase the uniform distribution of current and make for better electrical efficiency. It is realized that corrosion of the grids will discourage this change, but even if it could not be used in the positive grids, it might successfully be used in the negative grids where corrosion is comparatively slow. On the face of it this should greatly increase cooling through the lugs.

118. Since the electrolyte level has already been raised to a near maximum, l, the length of the heat transfer path, cannot be decreased to any appreciable extent, but A, the area the heat passes through, could be increased by making the area of the shoulders greater as they come through the cell top. Indications are that at present this change is not necessary because the area in the present design is sufficient to handle the heat which is being transferred, but if the changes in design mentioned were experimented with and found successful in enabling more rapid heat transfer, then perhaps increasing the area of the shoulders coming through the cell top would be beneficial.

119. The equation further suggests that by cooling the air passing over the finned bus-bars additional cooling could be obtained. This is borne out by the experimental work and would definitely have a great effect in keeping the cells cool.

120. By applying the same equation to cooling through the sides it can be seen that the cell jar could be designed to greatly facilitate cooling by this means. For example, k could be increased and l effectively decreased by building a thin copper plate into the sides near the electrolyte side with just enough rubber between the copper plate and the electrolyte to protect the plate. Fins, posts or some other copper arrangement could bring the heat outside to a copper plate over which a cooling air stream flowed. Again, Δt could be increased by cooling the air passing over.

121. Now all these changes in design might help the cooling to some extent, but they might and probably would be limited by the poor conductance of the electrolyte and the slowness of natural convection currents in the cell. If artificial stirring could be secured by some means it would go a long way toward increasing the cooling efficiency by any means, as indicated by the results obtained in this experimental work.

122. By a modification of the charging procedure it might be possible to take advantage of the natural stirring due to gassing for a much longer time than an hour for each cycle. If it were possible to charge the cell at a high enough rate so that the cell would be gassing about 15% of the amount it does at the regular finishing rate during the whole time of the charge, then the advantages to cooling as a result of stirring might be present for six or so hours instead of one or less. However, since this would shorten the time of charge it might also result in increased heating. However, if the additional cooling because of stirring would overbalance the additional heating due to increased I^2R drop over a shorter time period, then from the cooling standpoint this might make a good method of charge.

123. In connection with corrosion it should be remembered that if more efficient cooling can be secured the rate of corrosion will be slowed down, so that the idea of lead-coated copper grids, would be made more feasible.

124. The changes in design which have been discussed so far might be considered to be minor in scope in as much as they do not involve any overall change in the cell design. However, if a trial installation should be successful, then it will have been shown that the cumbersome duct system could be removed from the cell tops, and water-loss would be cut to a very small fraction of the present loss so that access to the cell tops would not have to be had so often, perhaps not at all if the watering could be made automatic. The present cell because of its long shape is inefficient electrically and thermally. There are indications that a square cell is the most efficient shape. Reducing the length should make cooling more efficient. Therefore, there might be big possibilities in cutting the size of the cells in half and using twice as many in a battery.

125. The experimental fin-bus-lug system is also capable of much improvement. By making the bus-bars between cells flat, the fins could be extended vertically into the air stream facilitating any necessary increase in area and probably better contact with the ventilating air. Indeed, by putting a top on the fins and by extending the flat bus-bars across the width of the cell instead of having several busses between cells, there would be a duct in which velocity of flow and volume could be nicely regulated. Of course,

this would be getting back to ducts again, but under quite different circumstances with no problem of adjusting individual flows in cells, no corrosion due to acid mist, and no more danger in the event of a casualty to the blower system than exists under the present system. Probably the danger would much less because there would be no electrolyte film which may be a source of explosions. The increased contact of air with the fins made possible by ducts would probably make for small ducts and a smaller volume of air necessary. Thus the proposed system might work into something fairly complex but with many advantages, and in any event simpler than the present system.

IV. CONCLUSIONS

126. In general it may be concluded that a method of ventilation has been developed which the experimental work indicates will compare favorably under service conditions with the present closed-cell system of ventilation.

127. The proposed system should be the equal of the present system in cooling the cell at ambient air temperatures as high as 90 - 95°F. Where air temperatures are below that, the system should be superior to the present system, indicating that any pre-cooling of the ventilating air which can be obtained will result in a lower average cell temperature.

128. It is estimated that from two to four times the present maximum volume of air must be supplied to the batteries and the air must be given a minimum linear velocity of 300 - 400 feet per minute over the tops of the cells.

129. The experimental work indicates that the proposed ventilation system has been developed to a close approach to the maximum efficiency, if no changes in the present cell design may be assumed.

130. If cooling through the sides could be employed it would be an appreciable aid to either system in cooling the cells, at least for batteries composed of cells of the Exide VLA-47 type. For that cell, cooling through the sides is appreciably more efficient for small temperature differentials than cooling through the lugs.

131. Under the closed-cell ventilation system the primary factor in cooling is evaporation of water from the electrolyte. No other means of cooling is capable of accounting for the effect achieved.

132. High humidities decrease the cooling efficiency of the closed-cell ventilation system.

133. Gassing, with consequent stirring of the electrolyte, increases

the efficiency of any means of cooling to a large extent, but increases the efficiency of cooling by evaporation more than by cooling through the lugs.

134. The greater the temperature differential between cell and air, the more favorable is the proposed system in comparison with the present, because the proposed system depends to a great degree on the temperature differential, while the present system is relatively independent of the temperature differential.

135. Cooling takes place faster at the top of the cell than in other portions by either means of cooling, at least during the first few hours of charge and the first few hours after the gassing phase of the charge. Temperature is indicated to be uniform during the gassing phase of the charge.

136. A simple, easy method of experimentally determining the heat capacity of a cell has been found. This enables quantitative calculations of heat transfer to be made.

137. Raising the electrolyte as high as possible in the cell is an important factor in cell cooling by the proposed method. It should give additional electrical capacity to the cell.

138. Water-loss in the proposed system can be kept down to almost that minimum due to electrolysis of the water during the gassing phase. In the closed-cell system, water-loss could be decreased by various devices, at the expense, however, of cooling efficiency.

139. No method has been discovered of absolutely preventing explosions in the individual cells - except of course by ventilation of the inside to the extent necessary, but this has been made unnecessary by the complete elimination of harmful effects of these explosions by the use of glass wool in the cell top.

140. Acid spray and electrolyte spillage can be reduced 100% in the proposed system on the basis of the experimental observations.

141. It is also concluded that while the method has been developed until a close approach to the maximum efficiency of cooling has been made if no changes in design are assumed, changes in design and battery operation might do much toward further increases in battery efficiency.

V. RECOMMENDATIONS.

142. On the basis of the conclusions derived from the experimental work, it is recommended that a trial installation of the proposed system be made on a submarine. It should be made in such a way that a comparison between the proposed system and the present closed-cell system could

be obtained.

143. If such an installation should prove to compare favorably with the present system under service conditions, it is further recommended that additional experimental work and changes in design be considered so that the efficiency of cooling in submarine cells could be developed to its fullest extent.

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(d) N.T.M.E. Confidential Report No. 310-45, dated July 1945.

(e) NRL Confidential Report No. P-1023, dated 2 February 1934.

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(h) NRL Report No. P-1243, dated 4 March 1936.

(i) NRL Report No. P-1113, dated 18 January 1935.

(j) Heat Transmission - McAdams-McGraw and Hill. (1933).

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(l) The Reaction Between Hydrogen and Oxygen - Hinschelwood and Williams. Oxford Press (1934).

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APPENDIX I

Estimated Magnitudes of the Cooling Factors.

1. Evaporation of Water from the Electrolyte.

Suppose dry air passing into the cell at a rate of 6 cubic feet per minute (CFM.) and at a temperature of 90°F., and coming out 50% saturated at 110°F. The vapor pressure of water is 65.5 millimeters of mercury at 110°F., consequently the water-loss under the assumed conditions will be 304 grams per hour. The heat of evaporation of water is approximately 577 calories per gram of water evaporated from electrolyte of 1250 specific gravity. Therefore, 577 x 304 = 175,000 gram calories, or 175 kilogram calories will be lost per hour by evaporation.

2. By Heat Exchange to the Ventilating Air.

The heat capacity of air is about 4.5 calories per cubic foot per degree Fahrenheit under the conditions concerned. Therefore, for 6 CFM and a 20 degree temperature rise (90° - 110°) the heat loss is calculated to be 6 x 60 x 4.5 x 20 = 32,000 gram calories or 32 kilogram calories per hour.

3. By the Cooling Effect of Air Passing Over the Top. Bottom and Sides of the Cell.

Assume for purposes of calculation that the air passing over the cell case keeps the outside temperature of the case at 90°F. while the electrolyte keeps the inside at 125°F. Then the quantity of heat transmitted can be calculated from the equation for heat transmission through a uniform body (reference (j)) page 10;

$$q = \frac{k A \Delta t}{l}$$

where q is the quantity of heat transmitted, k, the heat conductivity coefficient, A. the area the heat is conducted through, Δ t, the temperature difference between the faces, and l, the length of the path the heat traverses. A handbook value for the heat conductivity of hard rubber is 0.00055 calories per centimeter per second per degree Centigrade per centimeter square. The cell case has an area of 20 square feet and an average thickness of about 1/2 inch. The quantity of heat transmitted, calculated from the above equation if 566 kilogram calories per hour.

4. <u>By the Cooling Effect of Air Passing Over the Busses Connecting the Cells</u>.

In a Gould OWTX-49 there are eight lugs which can transmit heat from the plates and the electrolyte to the inter-cell connectors. Assuming that the top of the lug could be kept at 90°F. and that the lug is a bar of copper of uniform cross section 1 3/4 inches by 5/8 inches extending 3 inches down through the cell top into the electrolyte at which point its temperature is 125°F., the heat transferred through the lug can also be calculated from the above equation. The k value for copper is 0.918. The value calculated is 478 kilogram calories per hour for eight lugs.

5. <u>By Radiation from All Surfaces</u>.

Assuming that the cell is a perfect radiator the amount of heat which could be lost by radiation can be calculated by means of the equation (reference (j)) page 52:

$$q = 0.173 \, A \, E \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4 \right] \qquad 254,$$

where q is the quantity of heat radiated in calories per hour per square foot of surface, A and E are constants which are unity for the perfect radiator, and T_1 and T_2 are the absolute temperatures of the cell and surroundings. A value of 22 kilogram calories per hour for the cell is obtained when the cell is at 125°F. and the surroundings at 90°F. However, the cell is not a perfect radiator and under service conditions would be surrounded by other cells which would be at the same temperature as itself, consequently this value which is already small would become insignificant.

TABLE I

Cooling Through the Lugs - Plain Bus Bars.

No.	Equilibrium Temp. Degrees F.	Air Temp. ° F.	Electrolyte Level " Below Cell Top	Air Speed Over Busses Feet Per Minute (FPM)
1	* 125+	85	3 - 4	0
2	123	86	3 - 4	500
3	122	85	3 - 4	500
4	122	85	3 - 4	500
5	118	72	3 - 4	500
8	114	62	3 - 4	500
9	113	62	3 - 4	500

* Highest temperature recorded - still rising when run was stopped.

TABLE II

Cooling Through the Lugs - "75" Finned Bus Bars

No.	Equilibrium Temp. Degrees F.	Air Temp. ° F.	Electrolyte Level "Below Cell Top	Air Speed Over Busses Feet Per Minute
1	134	89	3	0
2	127	95	3	400
3	126	95	3	400
4	124	90	3	300
5	122	88	3	400
6	111	70	3	500
7	125	95	1	400
8	* 125	80	1	0
9	122	95	1	400
10	118	89	1	500
11	118	88	1	500
12	118	86	1	400
13	118	85	1	400
14	118	87	1	500
15	116	89	1	400
16	116	88	1	500
17	115	82	1	400
18	115	84	1	400
19	114	84	1	400
20	112	78	1	400
21	111	60	1	400
22	104	69	1	500

* Highest temperature recorded - still rising when run was stopped

TABLE III

Cooling Through the Lugs - "200" Finned Bus Bars

No.	Equilibrium Temp. Degrees F.	Air Temp. °F.	Electrolyte Level " Below Cell Top	Air Speed Over Busses Feet Per Minute
1	135	85	1	0
2	127	88	1	75
3	123	91	1	210
4	120	88	1	187
5	119	88	1	314
6	118	88	1	400
7	118	88	1	500
8	117	84	1	165
9	117	87	1	455
10	116	86	1	500
11	116	86	1	500
12	116	88	1	600
13	115	86	1	495
14	115	87	1	565
15	115	84	1	500
16	112	80	1	600
17	103	69	1	500

TABLE IV

Closed-Cell Ventilation

No.	Equilibrium Temp. ° F.	Air (Dry) Temp. ° F.	Volume of Ventilating Air Cubic Feet Per Minute
1	127	88	2
2	125	84	2
3	125	86	4
4	124	86	5
5	122	85	4
6	118	75	4
7	118	89	6
8	118	87	6
9	117	76	5
10	116	78	4

TABLE V

Lower Inflammable Limits of Hydrogen

No.	Pack Density of Glass Wool (Lbs. /cu. ft.)	Trial No.	Limiting Concentration of H_2 **		
			In Air	In O_2	In Air-O_2 Mixtures
1	0	1	7	6	---
		2	7	5	---
		Mean	7	5.5	---
2	2.48	1	20	---	---
		2	20	7	6
		3	20	8	---
		Mean	20	7.5	6
3	4.92	1	*	9	---
		2	*	---	19
		3	*	---	18
		Mean		9	18.5
4.	6.10	1		9	38
5	7.40	1		9	45
		2		9	44
		Mean		9	44.5
6	9.90	1		11	50

* No explosion at any concentration.
** Concentration of H_2 in Air - O_2 Mixtures designed to be that which would be produced by a gassing cell (Electrolyte Mixture) being swept out by air.

TABLE VI

Breakdown of Gould OWTX-49 Construction and Calculation
of Heat Capacity in Charged Condition

Total Weight Filled and Charged	1652#
Electrolyte (1280 Sp. Gravity)	318#
Dry Cell All Formed	1334#
Hard Rubber Jar (Almost Pure Rubber)	105#

Positive Plate Assembly

Total Weight	662#
Weight of Grid	300#
Weight of Bus	26.8#
Saddle	1.7#
Other Parts	7.2#
Copper	11#
Glass Mats	7.4#
Rubber Container	11.4#
Binding Strips (Rubber or Polystyrene)	6.1#
Rubber Gaskets	0.4#
PbO_2	290#

Negative Plate Assembly

Total Weight	430#
Grid	170#
Bus	30.1#
Saddle	1.7#
Copper	10#
Separators (Rubber)	35#
Support Rods "	2#
Active Material (Pb)	248.8#

HEAT CAPACITY CALCULATION

Material	Total Weight (Lbs.)	Specific Heat (Cals /Lb. 1°C)	Total Sp. Heat
Electrolyte	318	317.1	101,000
PbO_2	290	29.0	8,410
Pb	765.7	15.4	11,780
Copper	21	42.1	885
Rubber	159.9	149.2	23,800
Glass	7.4	72.5	537
		Total Cals. /°C.	146,412
		Total Cals. /°F.	81,300

TABLE VII

Breakdown of Exide VLA-47 Construction and Calculation
Of Heat Capacity in Charged Condition

Total Weight Filled and Charged	1642#
Electrolyte (1250 Specific Gravity)	344#
Hard Rubber Jar (Almost Pure Rubber)	105#

Positive Plate Assembly

Total Weight Formed and Dried Including Terminals	698#
Active Material	308#
Core Rods (12% Pb-Sb Alloy)	223#
Total Tubes at 27 Rubber Tubes per Plate	50.7#
Copper	10#
Shoulders	21#

Negative Plate Assembly

Total Weight	452#
One Grid	171/4#
58% of Grid = Active Material.	
Separators (Rubber)	$23\frac{1}{2}$#
Copper	10#
Shoulders	38#
Grids (Pb-Sb Alloy - Pb Active Material)	414#

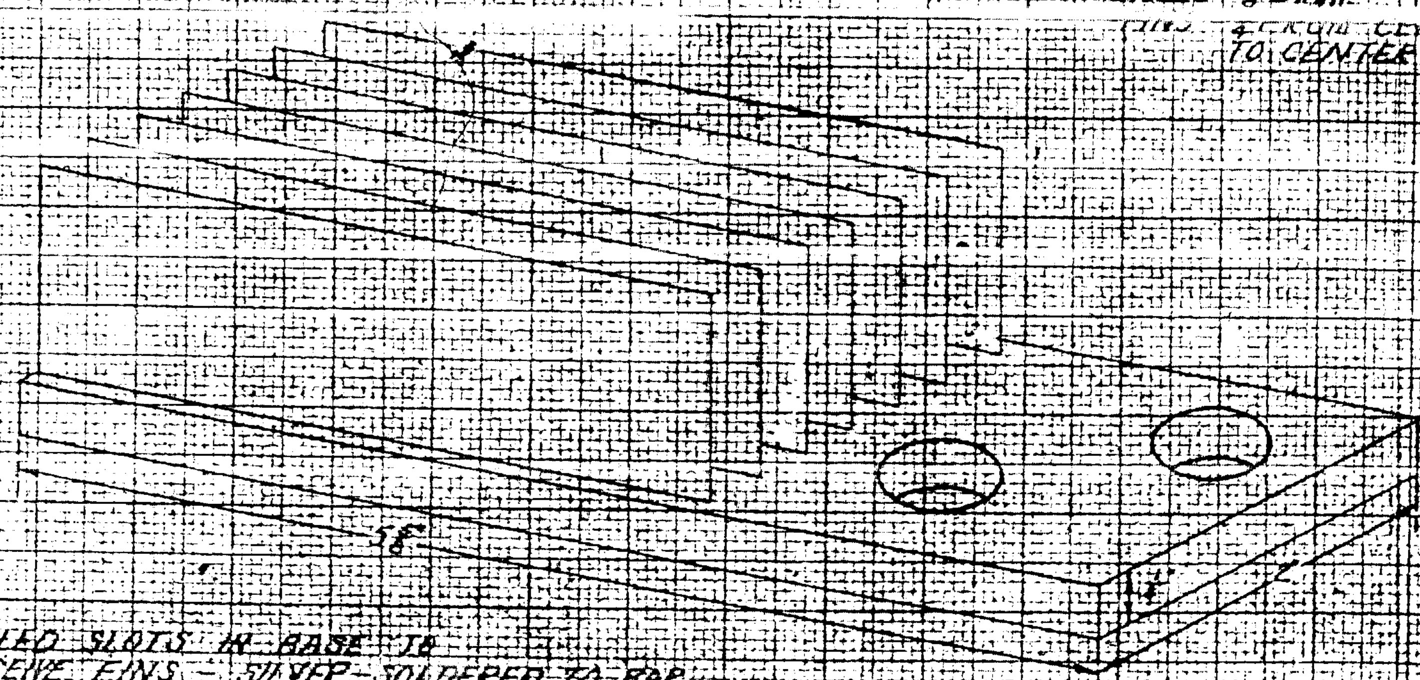
The sum of the weights of the parts is 20# short of the total weight. Therefore, 20 x the specific heat per pound of the cell is added as a correction factor. The breakdown is not as complete as that for the Gould Cell in Table VI, so some estimation of the weights of various parts was necessary. The possible error introduced is less than 5%.

Heat Capacity Calculation

Material	Total Weight (Lbs.)	Specific Heat (Cals /Lb.°C)	Total Sp. Heat
Electrolyte	344	317.1	109,000
Rubber	179.2	149.2	26,750
PbO_2	308	29	8,940
Grids & Pb(Act. Mat'l)	771.3	15.4	11,880
Correction	20	97.5	1,950
		Total Calories /°C.	158,520
		Heat Capacity Calories /°F.	88,200

DESIGN OF THE 75 FINNED BUSBARS

FINS 11 3/4 X 1/4
HOLES 5/8 DIAM
FINS 1/2 FROM CENTER TO CENTER

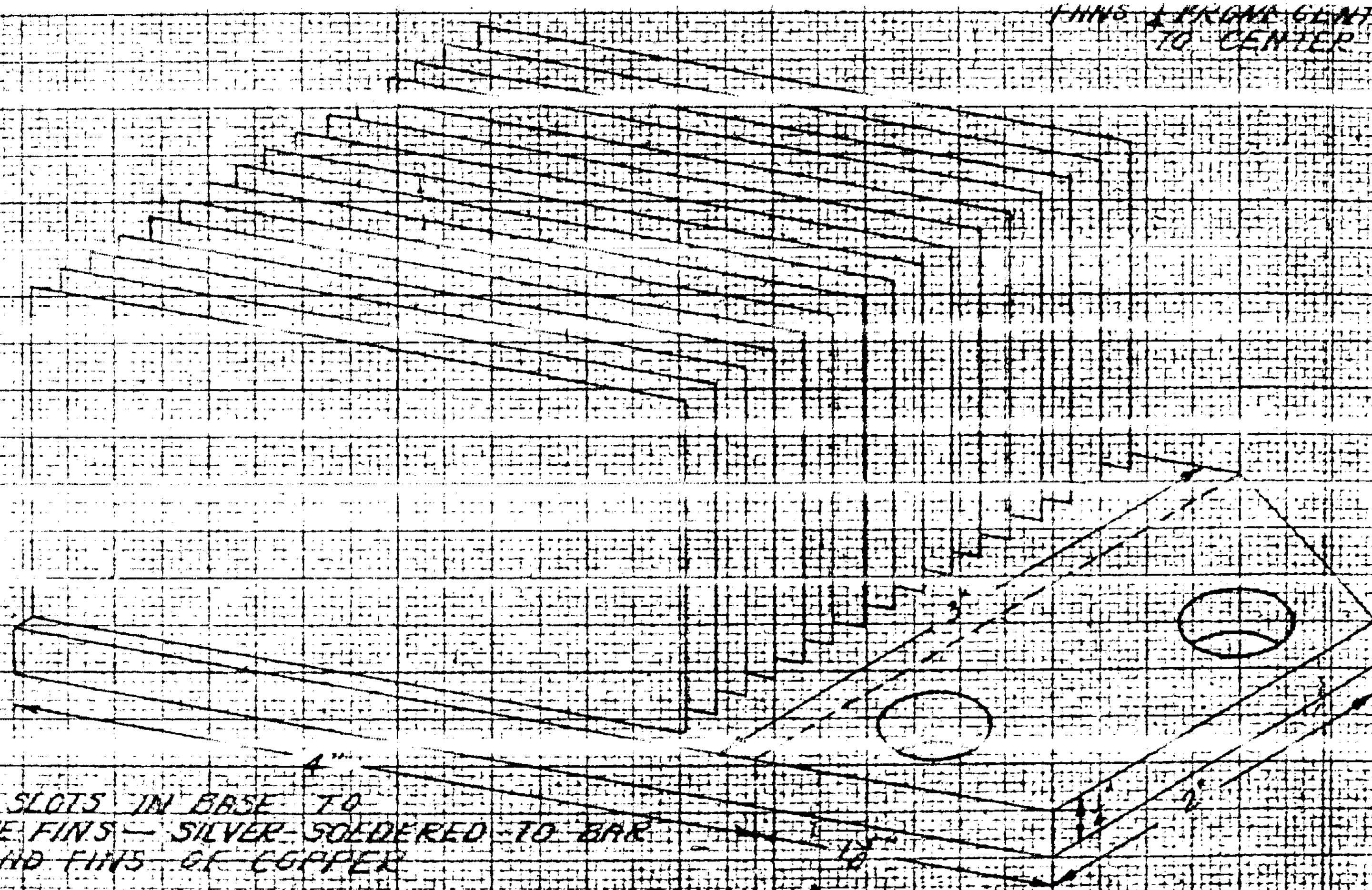


MILLED SLOTS IN BASE TO
RECEIVE FINS - SILVER SOLDERED TO BAR
BAR AND FINS OF COPPER

PLATE I

DESIGN OF THE "2BB" FINNED BUS BARS

FINS - $1\frac{1}{2}$" X $3\frac{1}{2}$" X $\frac{1}{32}$"
HOLES $\frac{5}{8}$" DIAM.
FINS $\frac{1}{4}$" FROM CENTER TO CENTER



MILLED SLOTS IN BASE TO
RECEIVE FINS — SILVER SOLDERED TO BAR
BAR AND FINS OF COPPER

PLATE 2

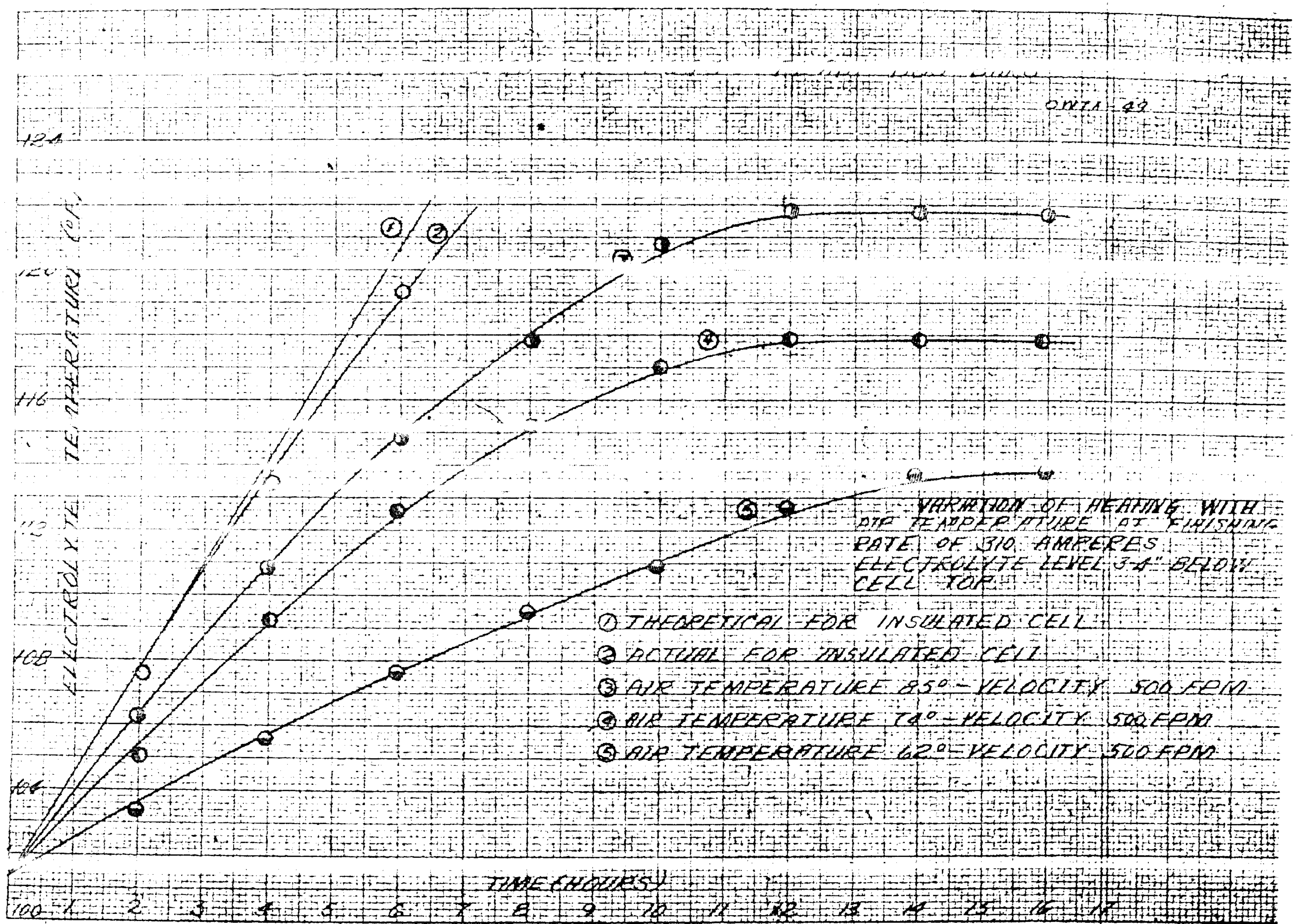

VARIATION OF HEATING WITH AIR TEMPERATURE AT FINISHING RATE OF 310 AMPERES
ELECTROLYTE LEVEL 3-4" BELOW CELL TOP
① THEORETICAL FOR INSULATED CELL
② ACTUAL FOR INSULATED CELL
③ AIR TEMPERATURE 85° - VELOCITY 500 FPM
④ AIR TEMPERATURE 74° - VELOCITY 500 FPM
⑤ AIR TEMPERATURE 62° - VELOCITY 500 FPM
ELECTROLYTE TEMPERATURE (°F)
TIME (HOURS)
100
104
108
112
116
120
124
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

PLATE 3

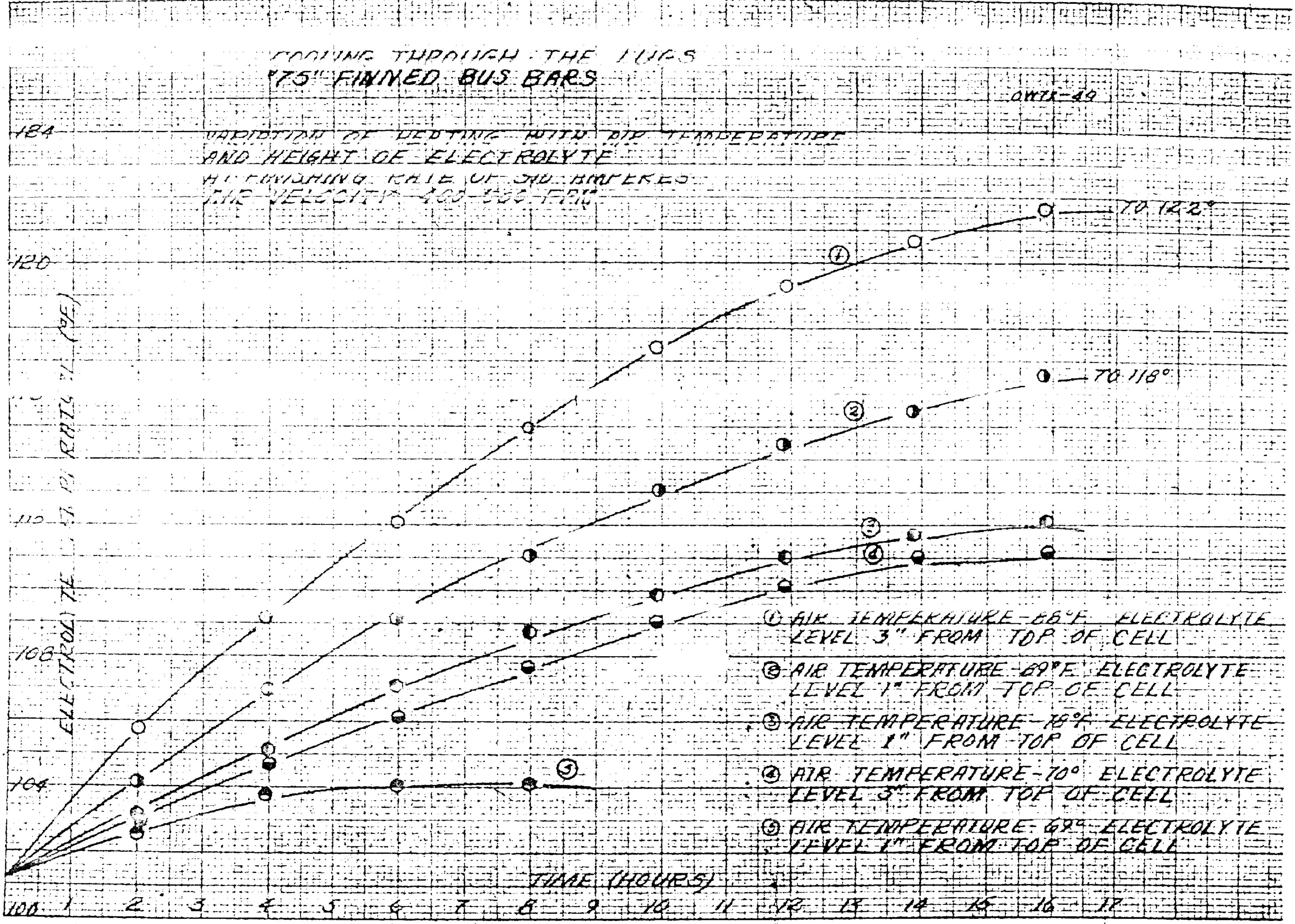

COOLING THROUGH THE LUGS
"75" FINNED BUS BARS
QWTX-49
AND HEIGHT OF ELECTROLYTE
70 122°
70 118°
① AIR TEMPERATURE-68°F ELECTROLYTE LEVEL 3" FROM TOP OF CELL
② AIR TEMPERATURE-69°F ELECTROLYTE LEVEL 1" FROM TOP OF CELL
③ AIR TEMPERATURE-78°F ELECTROLYTE LEVEL 1" FROM TOP OF CELL
④ AIR TEMPERATURE-70° ELECTROLYTE LEVEL 3" FROM TOP OF CELL
⑤ AIR TEMPERATURE-69° ELECTROLYTE LEVEL 1" FROM TOP OF CELL
TIME (HOURS)
100
104
108
120
124
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

PLATE 4

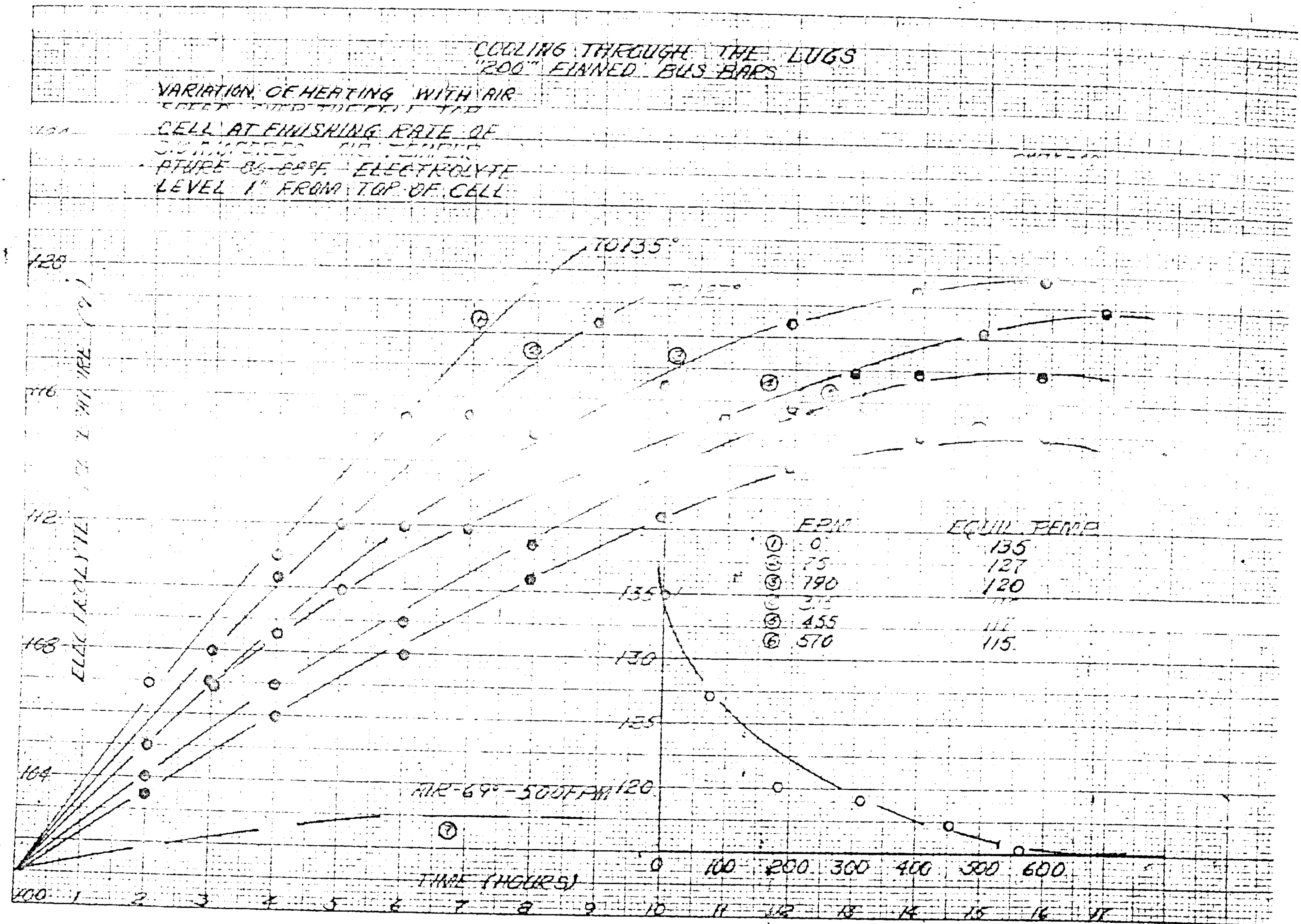

COOLING THROUGH THE LUGS
"200" FINNED BUS BARS
VARIATION OF HEATING WITH AIR
CELL AT FINISHING RATE OF
ATURE 86-88°F. ELECTROLYTE
LEVEL 1" FROM TOP OF CELL
TO 135°
FPM
EQUIL TEMP
① 0 135
③ 790 120
⑤ 455
⑥ 570 115
AIR-69°-500 FPM
TIME (HOURS)

PLATE 5

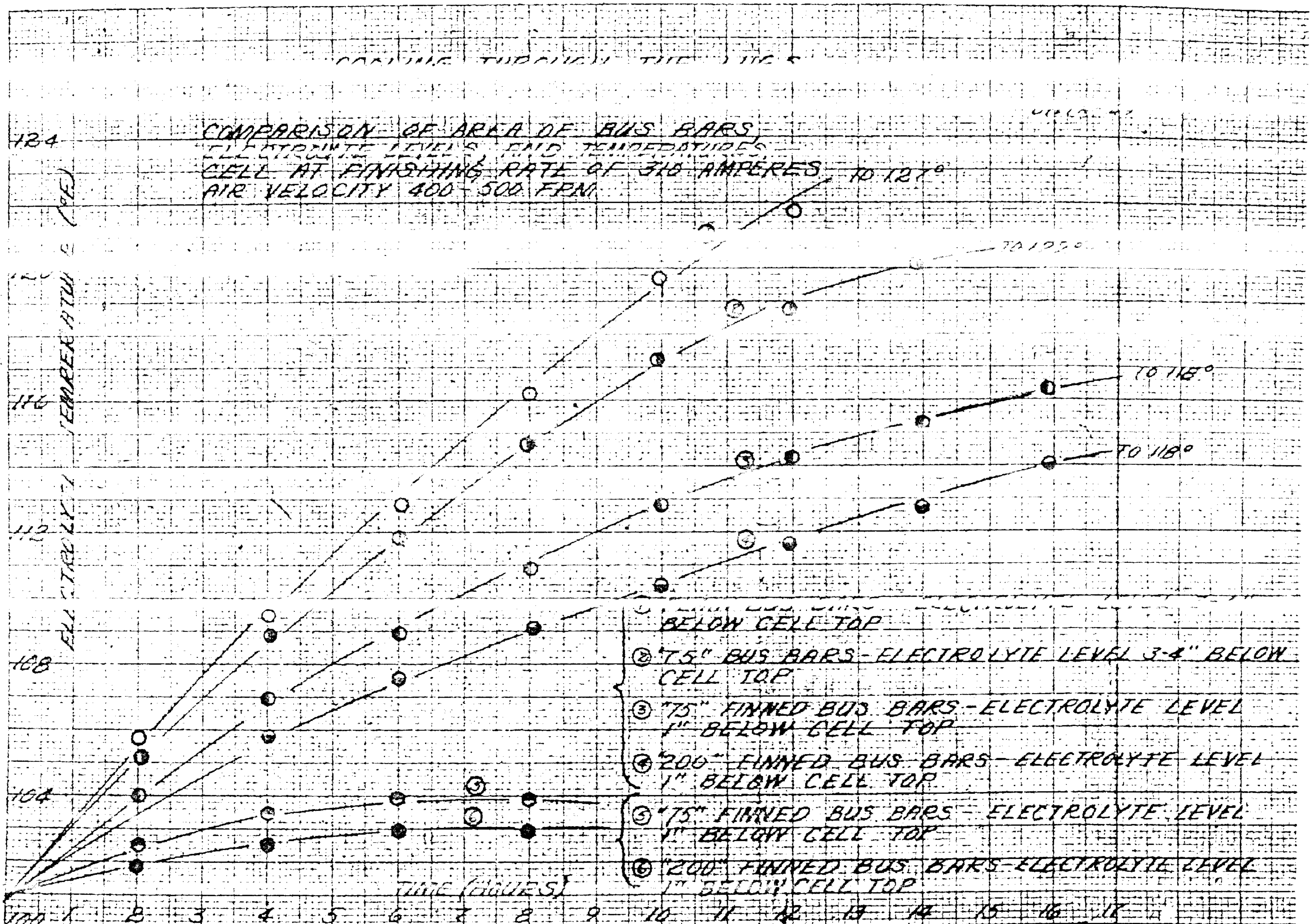
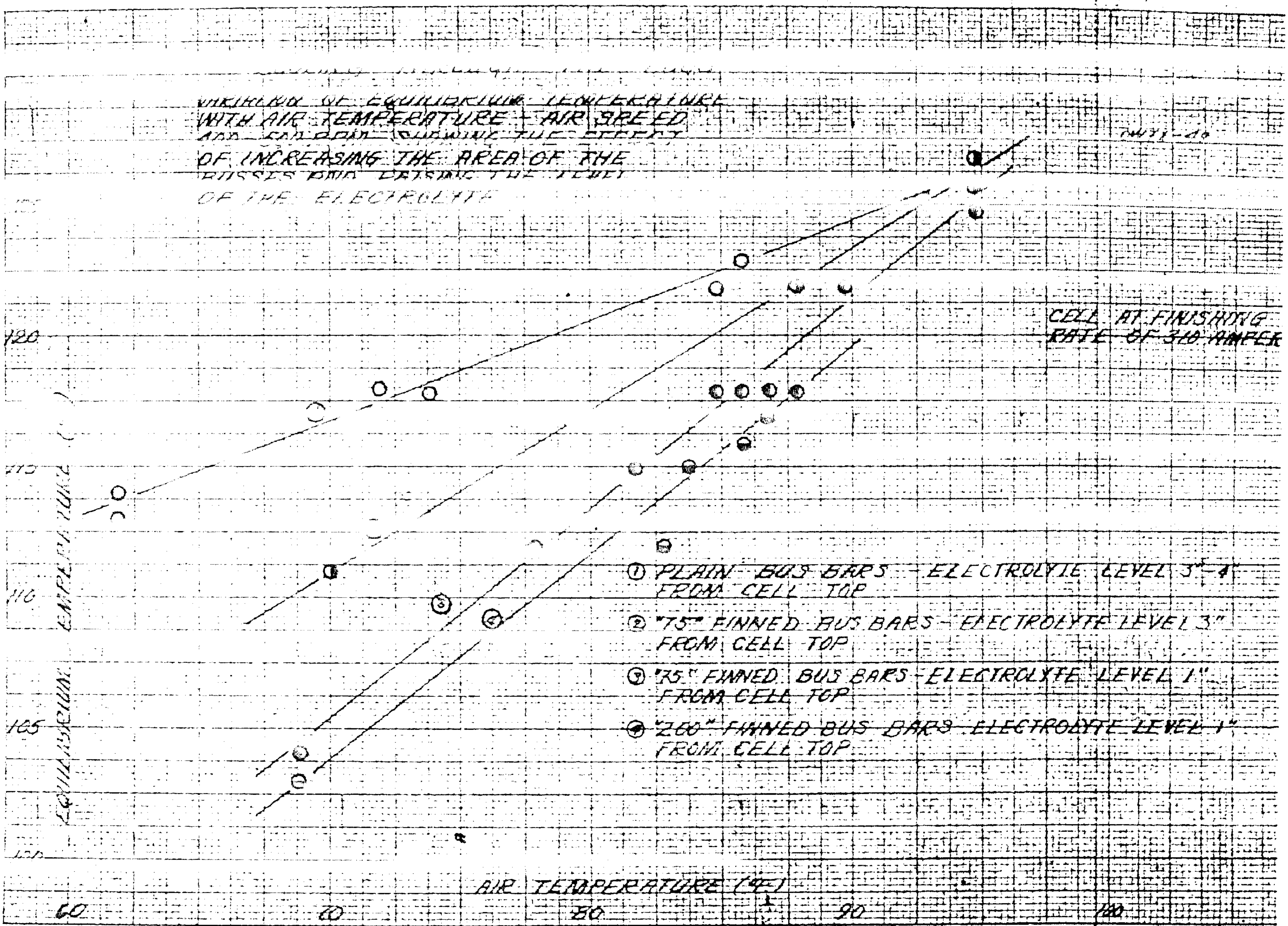

COMPARISON OF AREA OF BUS BARS,
CELL AT FINISHING RATE OF 310 AMPERES
AIR VELOCITY 400-500 FPM
TO 127°
TO 118°
TO 118°
BELOW CELL TOP
② "75" BUS BARS - ELECTROLYTE LEVEL 3-4" BELOW CELL TOP
③ "75" FINNED BUS BARS - ELECTROLYTE LEVEL 1" BELOW CELL TOP
④ "200" FINNED BUS BARS - ELECTROLYTE LEVEL 1" BELOW CELL TOP
⑤ "75" FINNED BUS BARS - ELECTROLYTE LEVEL 1" BELOW CELL TOP
⑥ "200" FINNED BUS BARS - ELECTROLYTE LEVEL 1" BELOW CELL TOP
124
116
112
108
104
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

PLATE 6



WITH AIR TEMPERATURE - AIR SPEED
OF INCREASING THE AREA OF THE
OF THE ELECTROLYTE
CELL AT FINISHING RATE OF 310 AMPER
① PLAIN BUS BARS - ELECTROLYTE LEVEL 3"-4" FROM CELL TOP
② "75" FINNED BUS BARS - ELECTROLYTE LEVEL 3" FROM CELL TOP
③ "75" FINNED BUS BARS - ELECTROLYTE LEVEL 1" FROM CELL TOP
④ "200" FINNED BUS BARS - ELECTROLYTE LEVEL 1" FROM CELL TOP
AIR TEMPERATURE (°F)
60
70
80
90
100
120
110
105

PLATE 7

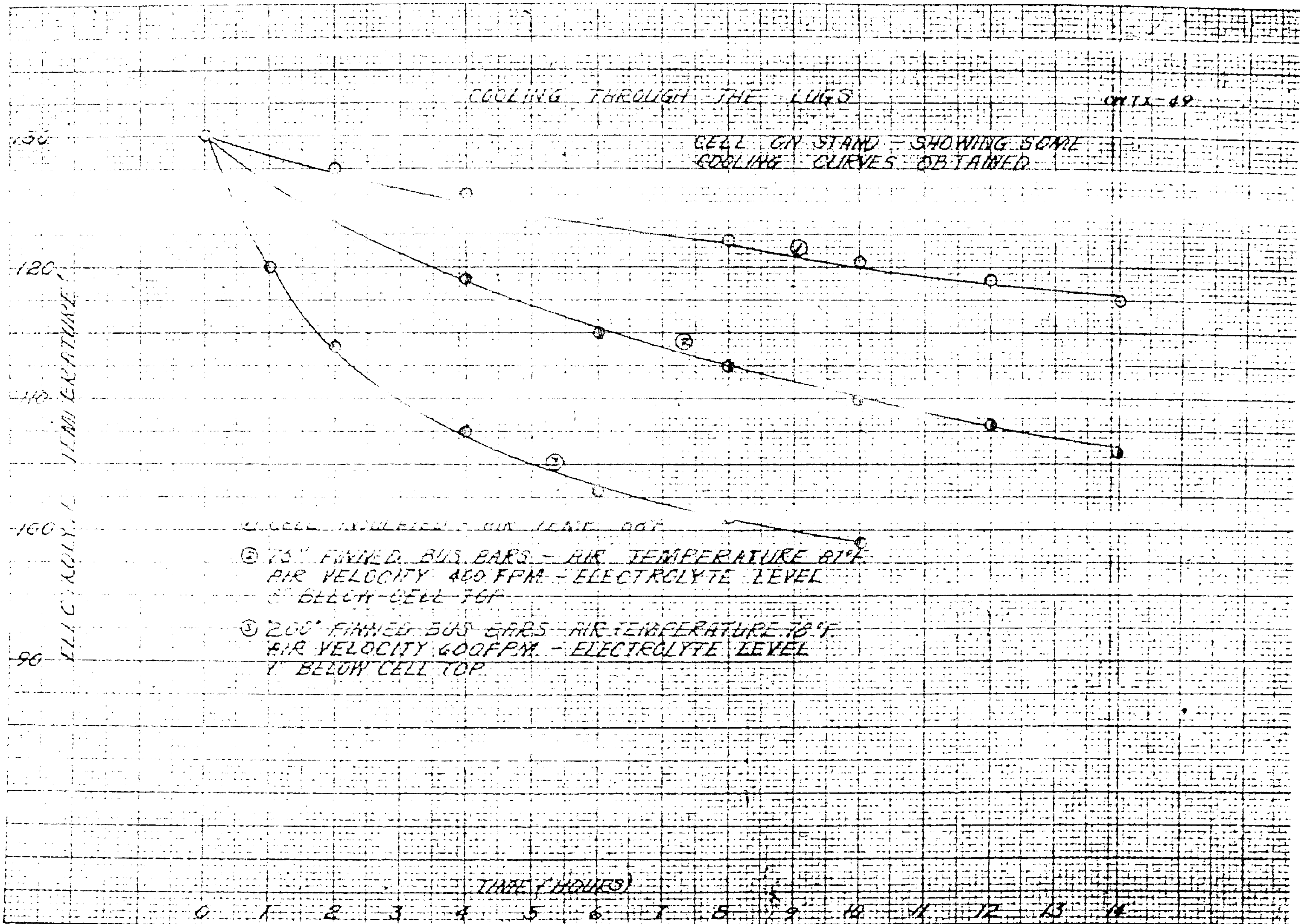

COOLING THROUGH THE LUGS
CELL ON STAND - SHOWING SOME COOLING CURVES OBTAINED
② 75" FINNED BUS BARS - AIR TEMPERATURE 81°F AIR VELOCITY 400 FPM - ELECTROLYTE LEVEL
③ 200" FINNED BUS BARS - AIR TEMPERATURE 78°F AIR VELOCITY 600FPM - ELECTROLYTE LEVEL 1" BELOW CELL TOP
120
110
100
90
TIME (HOURS)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

PLATE 8

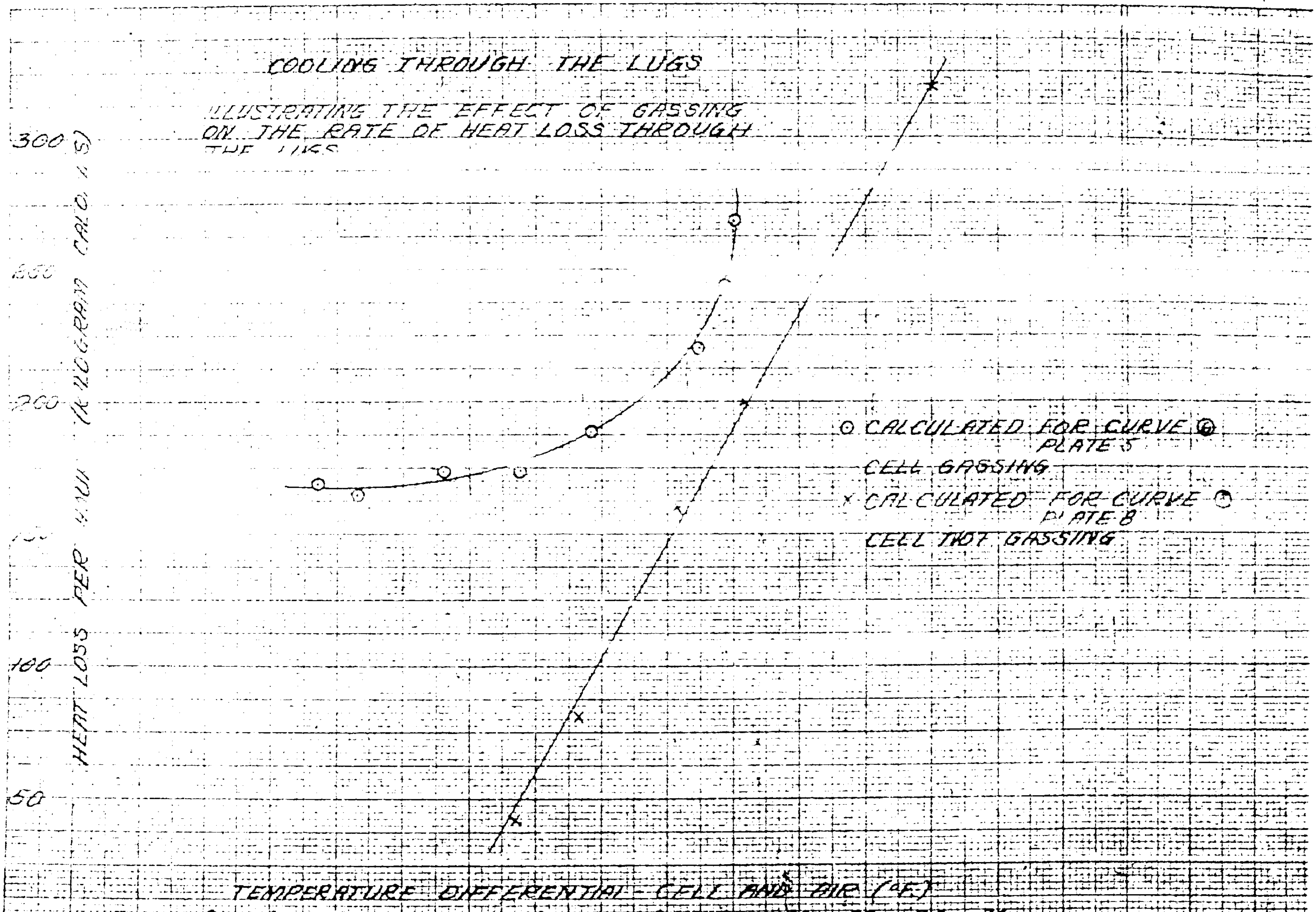

COOLING THROUGH THE LUGS
ILLUSTRATING THE EFFECT OF GASSING ON THE RATE OF HEAT LOSS THROUGH THE LUGS
⊙ CALCULATED FOR CURVE ⊙ PLATE 5
CELL GASSING
× CALCULATED FOR CURVE ⊙ PLATE 8
CELL NOT GASSING
HEAT LOSS PER HOUR (KILOGRAM CALORIES)
300
200
100
50
TEMPERATURE DIFFERENTIAL - CELL AND AIR (°F)
0
10
12
14
16
18
20
22
24
26
28
30
32
34
36

PLATE 9

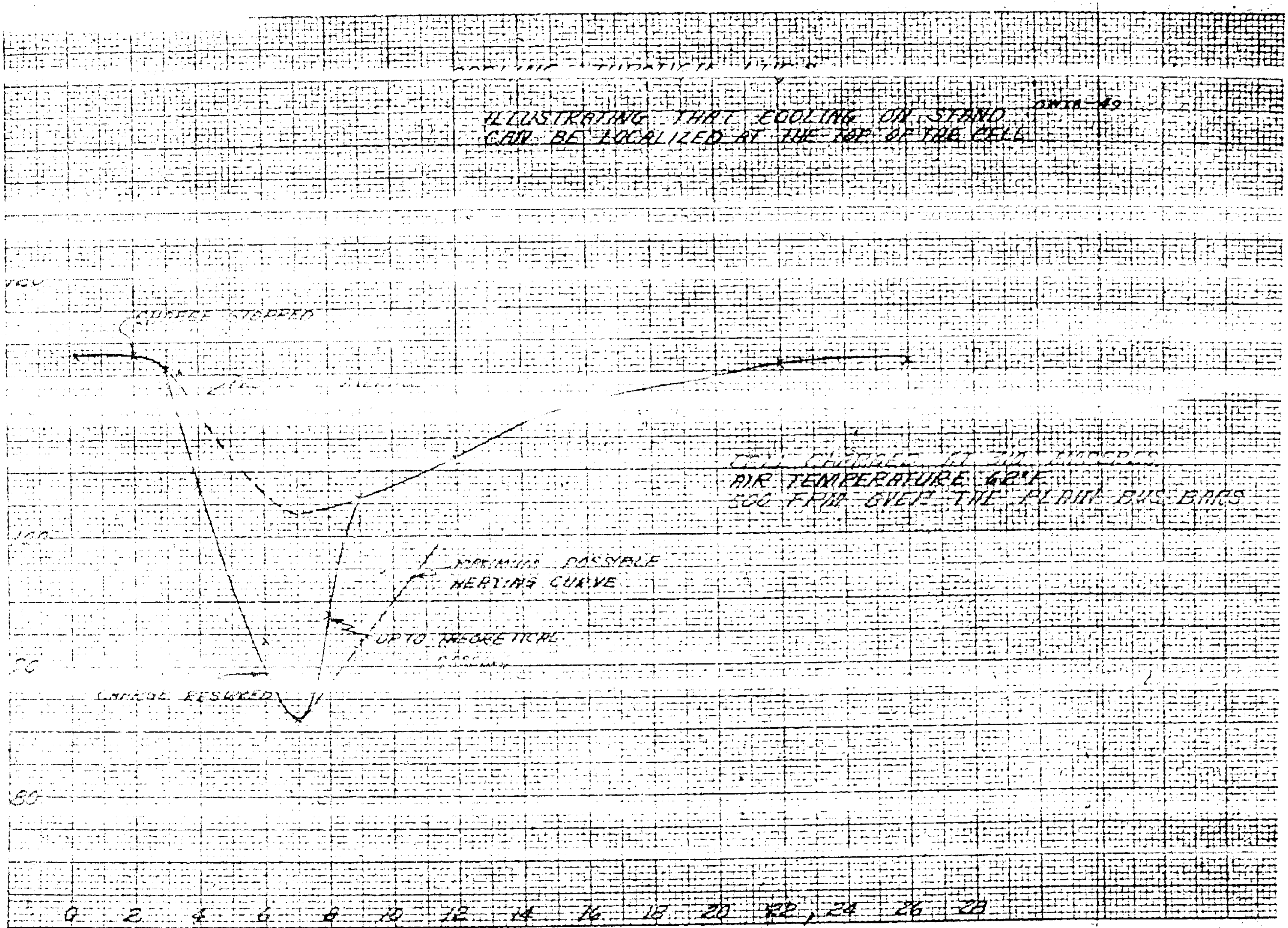

ILLUSTRATING THAT COOLING ON STAND
CAN BE LOCALIZED AT THE TOP OF THE CELL
CHARGE STOPPED
AIR TEMPERATURE 62°F
MAXIMUM POSSIBLE
HEATING CURVE
UP TO THEORETICAL
CHARGE RESUMED
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

PLATE 10

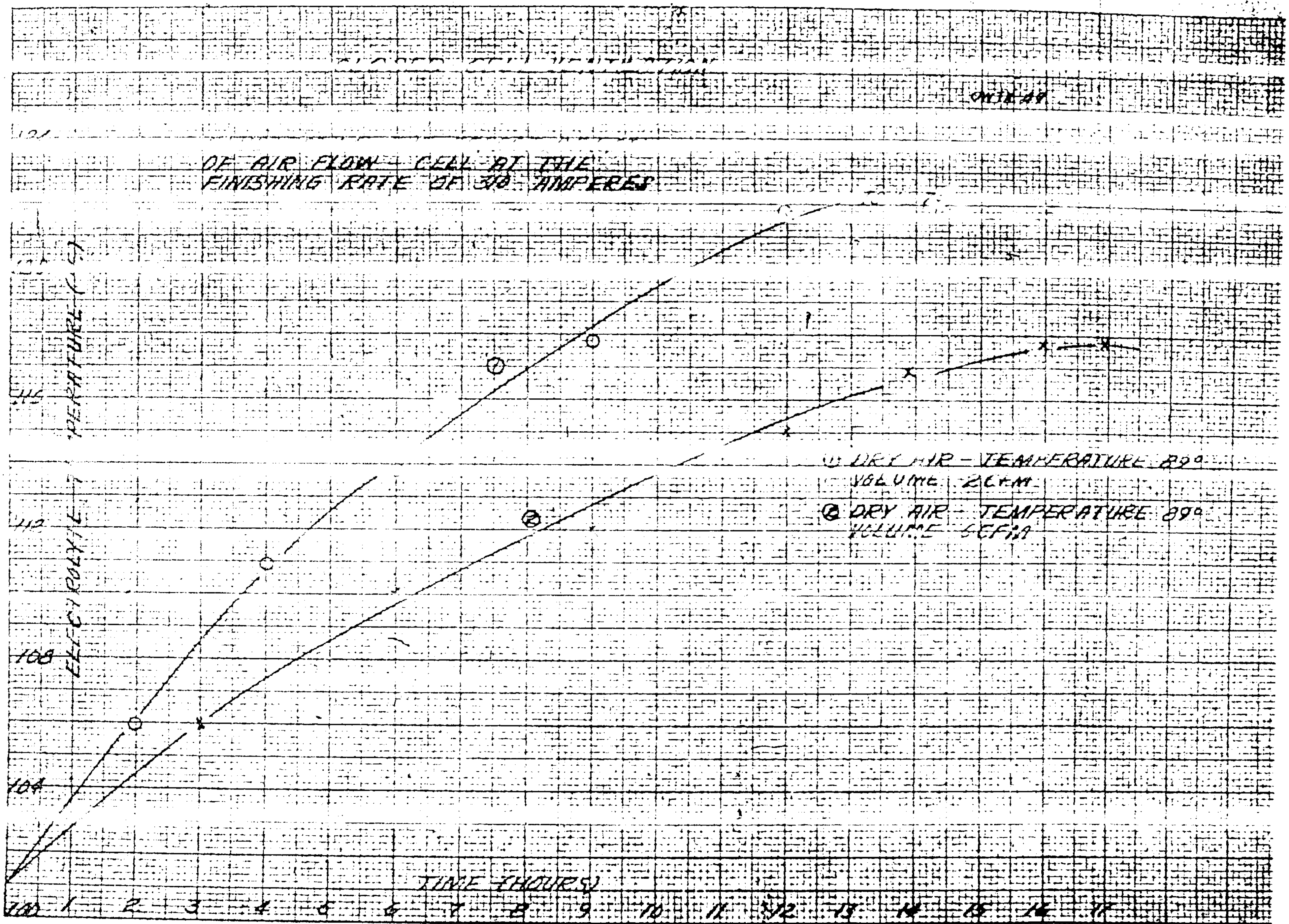

OF AIR FLOW - CELL AT THE
FINISHING RATE OF 30 AMPERES
① DRY AIR - TEMPERATURE 89°
VOLUME 2CFM
② DRY AIR - TEMPERATURE 89°
VOLUME 5CFM
ELECTROLYTE TEMPERATURE (°C)
116
112
108
104
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
TIME (HOURS)

PLATE 11

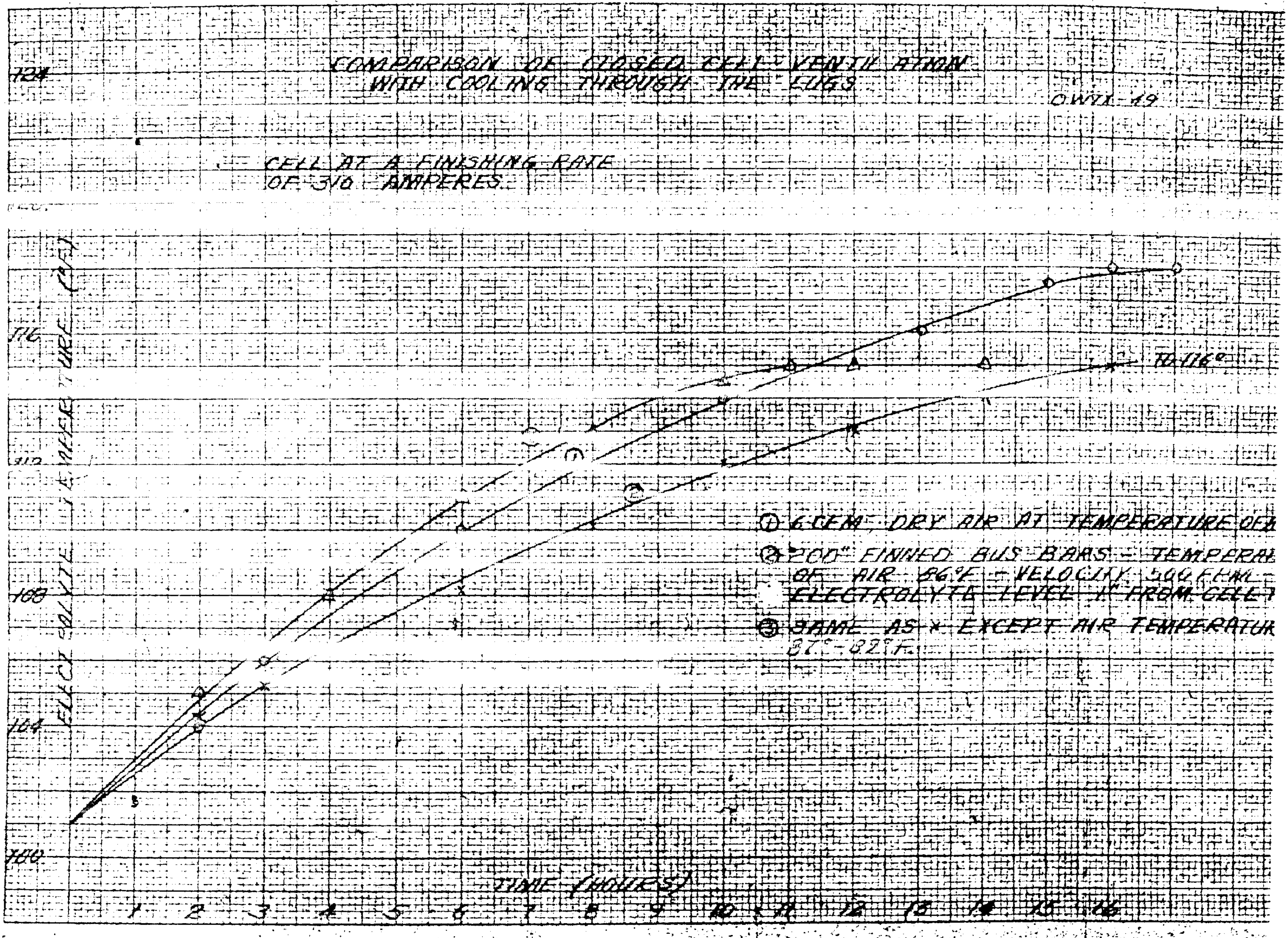

COMPARISON OF CLOSED CELL VENTILATION
WITH COOLING THROUGH THE LUGS
OWYI-49
CELL AT A FINISHING RATE
OF 310 AMPERES
ELECTROLYTE TEMPERATURE (°F)
TIME (HOURS)
TO 116°
① 6 CFM, DRY AIR AT TEMPERATURE OF
② 200" FINNED BUS BARS - TEMPERA
OF AIR 86°F - VELOCITY 500 FPM -
ELECTROLYTE LEVEL 1" FROM CELL T
③ SAME AS × EXCEPT AIR TEMPERATUR
87°-82°F
100
104
108
112
116
124
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

PLATE 12

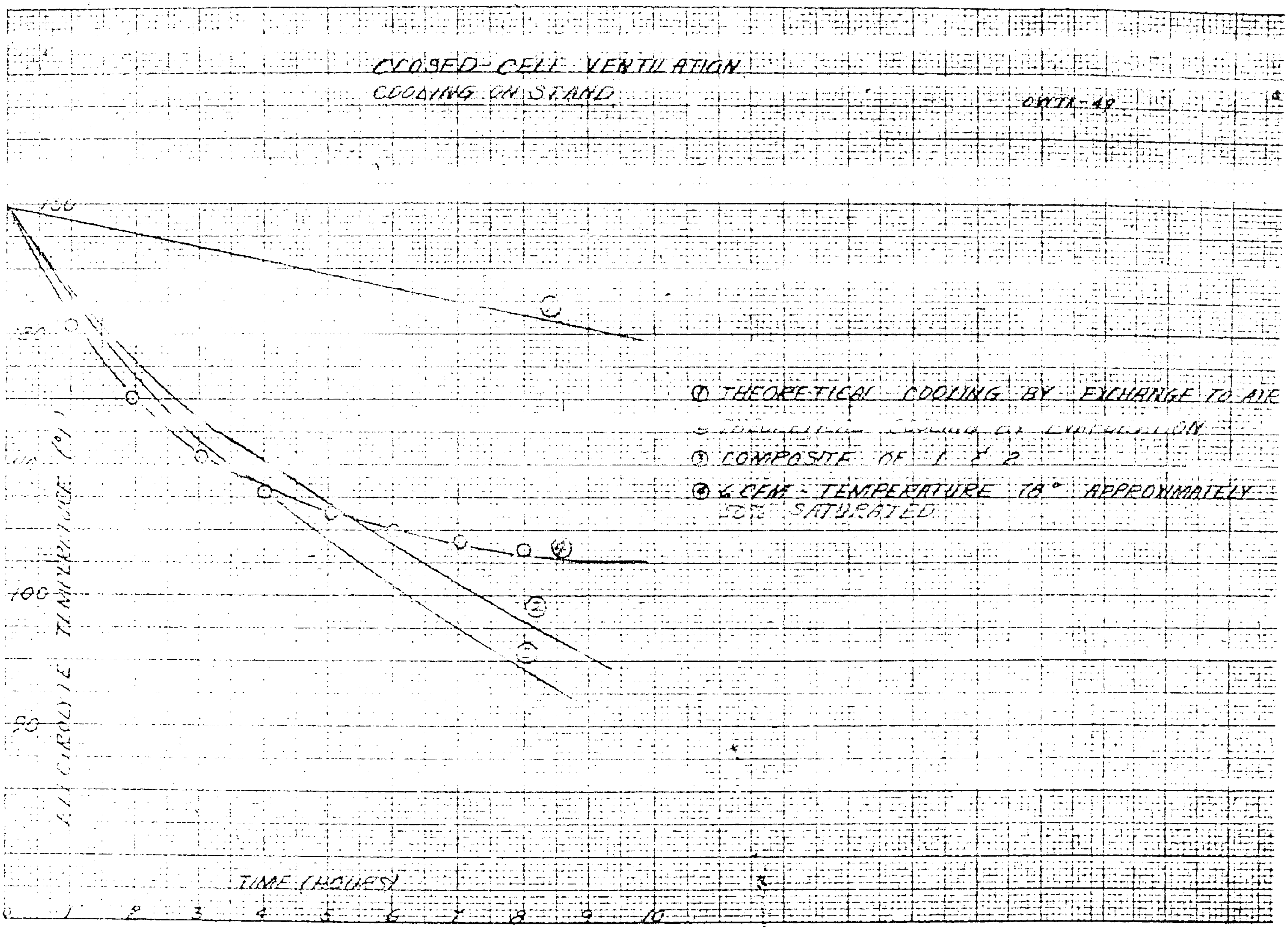

CLOSED-CELL VENTILATION
COOLING ON STAND
OWTK-49
① THEORETICAL COOLING BY EXCHANGE TO AIR
③ COMPOSITE OF 1 & 2
④ 6 CFM - TEMPERATURE 78° APPROXIMATELY
SATURATED
TIME (HOURS)
100
0
1
2
3
4
5
6
7
8
9
10

PLATE 13

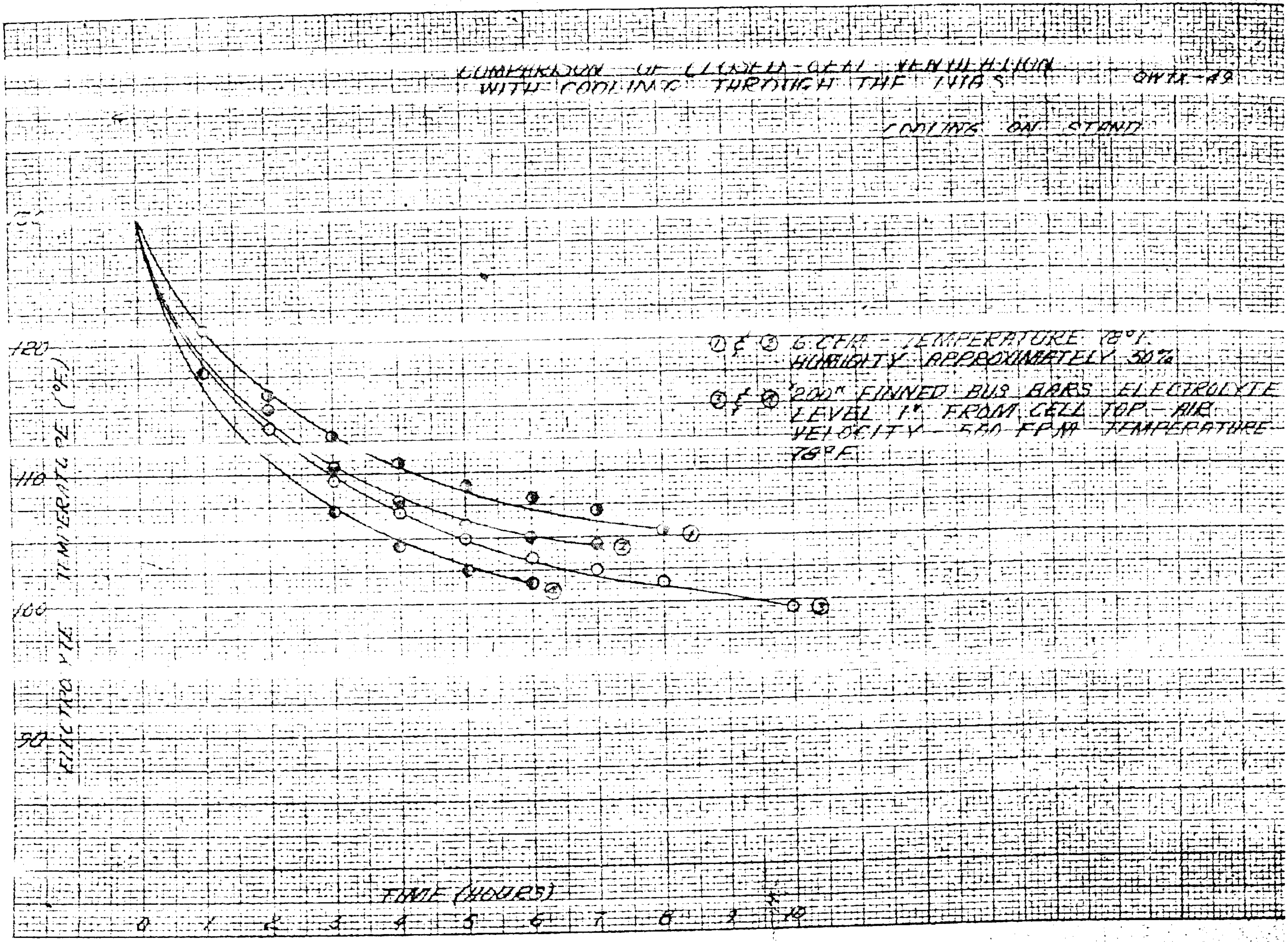
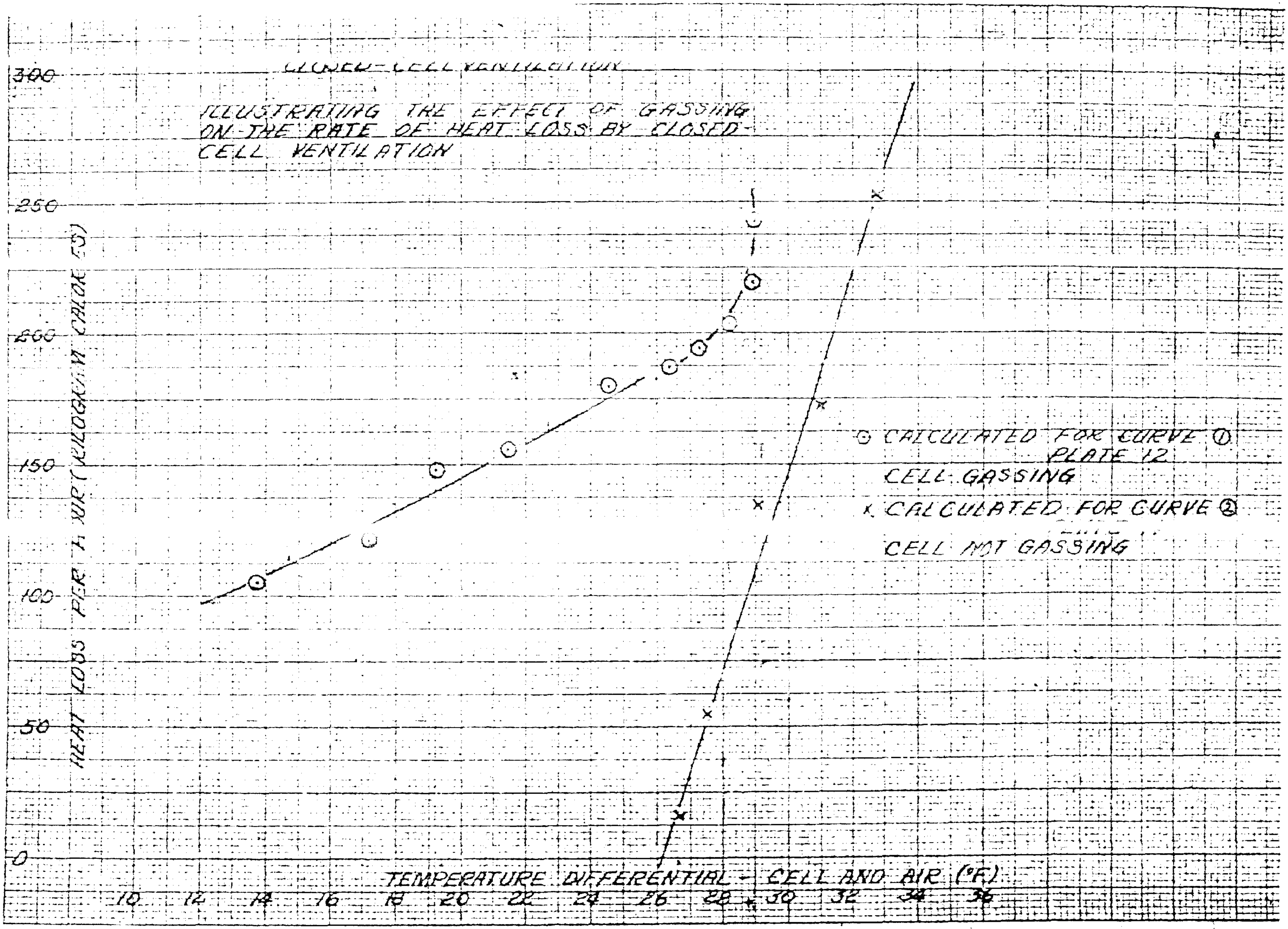

WITH COOLING THROUGH THE
QW1X-49
COOLING ON STAND
① & ② 6 CFM - TEMPERATURE 78°F
HUMIDITY APPROXIMATELY 30%
③ & ④ "200" FINNED BUS BARS ELECTROLYTE
LEVEL 1" FROM CELL TOP - AIR
VELOCITY - 550 FPM TEMPERATURE
78°F
ELECTROLYTE TEMPERATURE (°F)
120
110
100
90
TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10

PLATE 14



CLOSED-CELL VENTILATION
ILLUSTRATING THE EFFECT OF GASSING ON THE RATE OF HEAT LOSS BY CLOSED-CELL VENTILATION
HEAT LOSS PER HOUR (KILOGRAM CALORIES)
300
250
200
150
100
50
0
TEMPERATURE DIFFERENTIAL - CELL AND AIR (°F.)
10
12
14
16
18
20
22
24
26
28
30
32
34
36
CALCULATED FOR CURVE ① PLATE 12
CELL GASSING
CALCULATED FOR CURVE ②
CELL NOT GASSING

PLATE 15

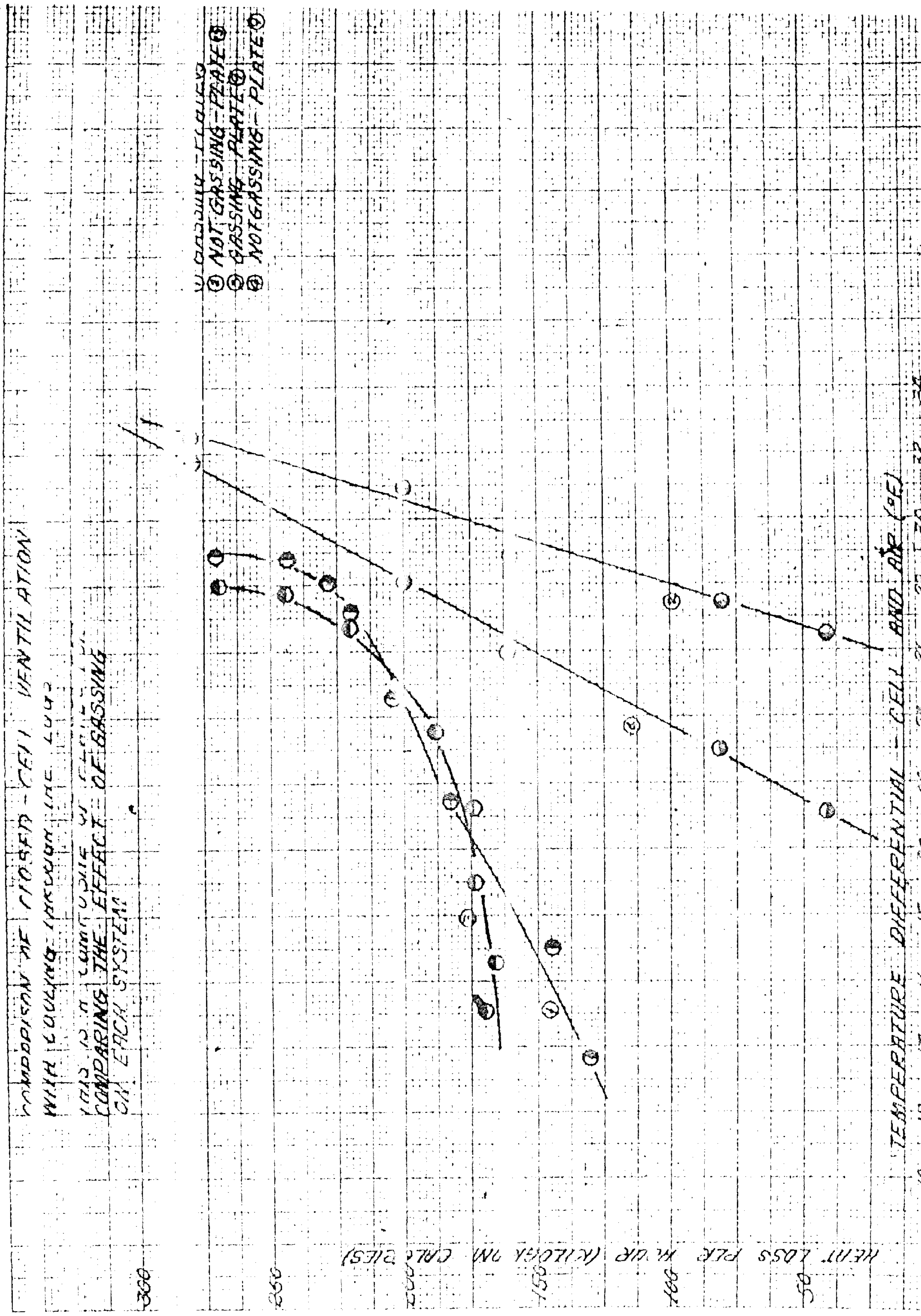

WITH COOLING THROUGH THE LUGS
COMPARING THE EFFECT OF GASSING
ON EACH SYSTEM
NOT GASSING - PLATE
GASSING - PLATE
NOTGASSING - PLATE
TEMPERATURE DIFFERENTIAL - CELL AND AIR (°F)
10
12
16
18
20
22
24
26
28
30
32
34
0
50
100
150
200
250
300

PLATE 16

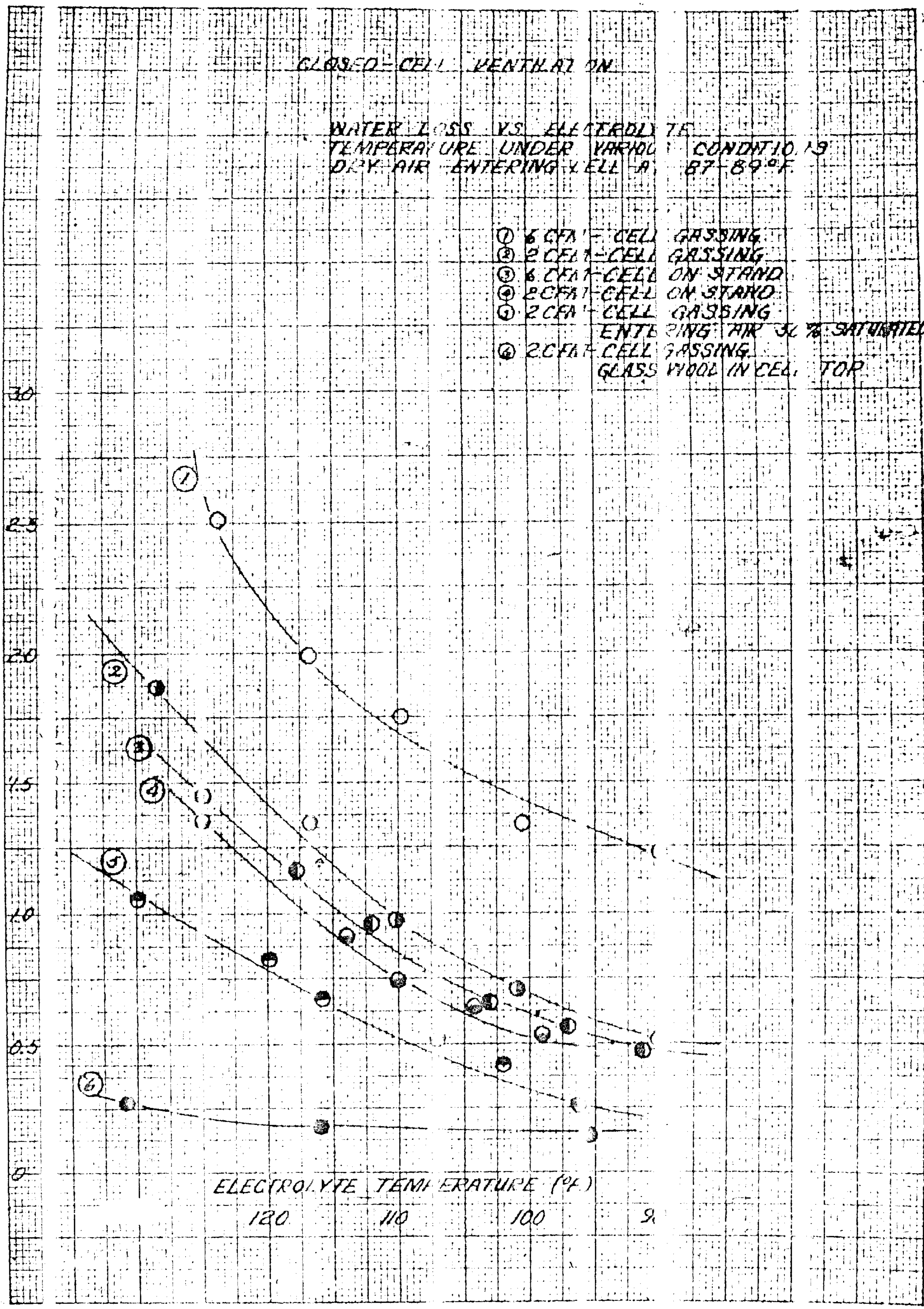

CLOSED-CELL VENTILATION
WATER LOSS VS. ELECTROLYTE TEMPERATURE UNDER VARIOUS CONDITIONS
DRY AIR ENTERING CELL AT 87-89°F
① 6 CFM - CELL GASSING
② 2 CFM - CELL GASSING
③ 6 CFM - CELL ON STAND
④ 2 CFM - CELL ON STAND
⑤ 2 CFM - CELL GASSING ENTERING AIR 50% SATURATED
⑥ 2 CFM - CELL GASSING GLASS WOOL IN CELL TOP
3.0
2.5
2.0
1.5
1.0
0.5
0
ELECTROLYTE TEMPERATURE (°F)
120
110
100

PLATE 17

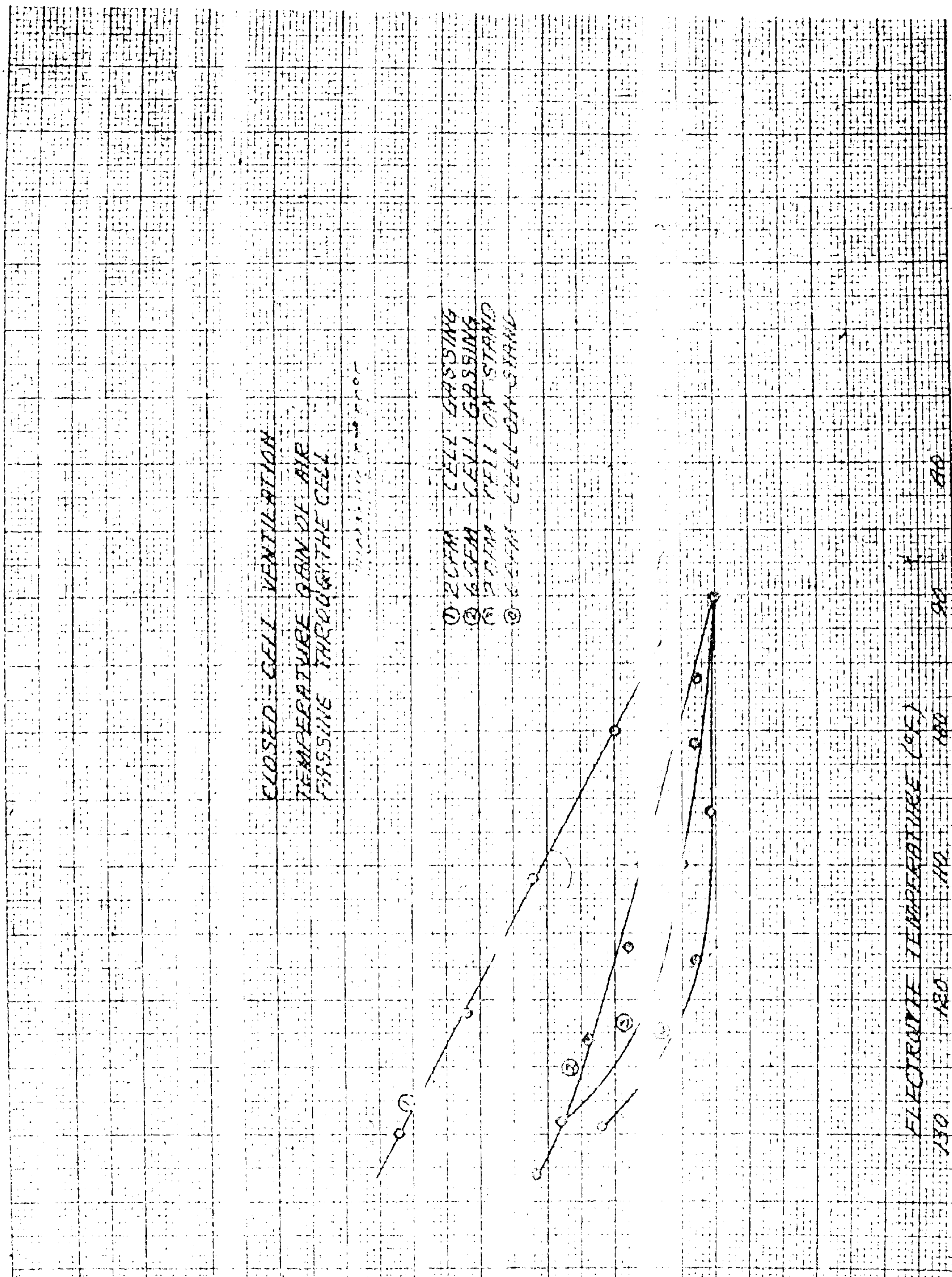

CLOSED - CELL VENTILATION
TEMPERATURE GAIN OF AIR
PASSING THROUGH THE CELL
① 2CFM - CELL GASSING
② 6CFM - CELL GASSING
③ 2CFM - CELL ON STAND
④ 6CFM - CELL ON STAND
ELECTROLYTE TEMPERATURE (°F)
130
120
110
100
90
80
40
20
10
0

PLATE 18

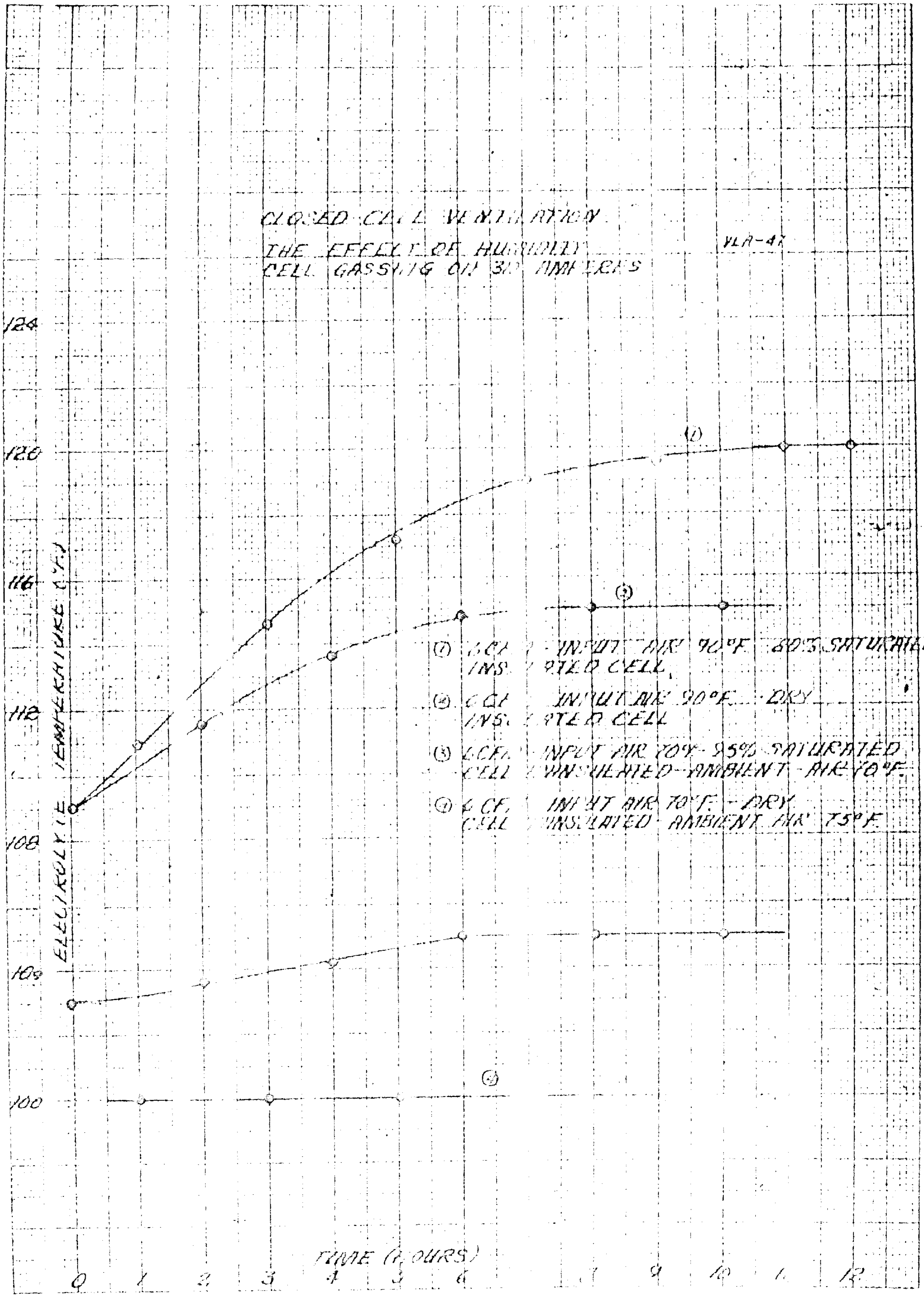

CLOSED CELL VENTILATION
THE EFFECT OF HUMIDITY
CELL GASSING ON 30 AMPERES
VLA-47
ELECTROLYTE TEMPERATURE (°F.)
124
120
116
112
108
104
100
TIME (HOURS)
0
1
2
3
4
5
6
9
10
12
(1)
(2)
(3)
(4)
INPUT AIR 90°F 80% SATURATED
INSULATED CELL
INPUT AIR 90°F DRY
INSULATED CELL
INPUT AIR 70°F 95% SATURATED
CELL UNINSULATED AMBIENT AIR 70°F
INPUT AIR 70°F DRY
CELL UNINSULATED AMBIENT AIR 75°F

PLATE 19

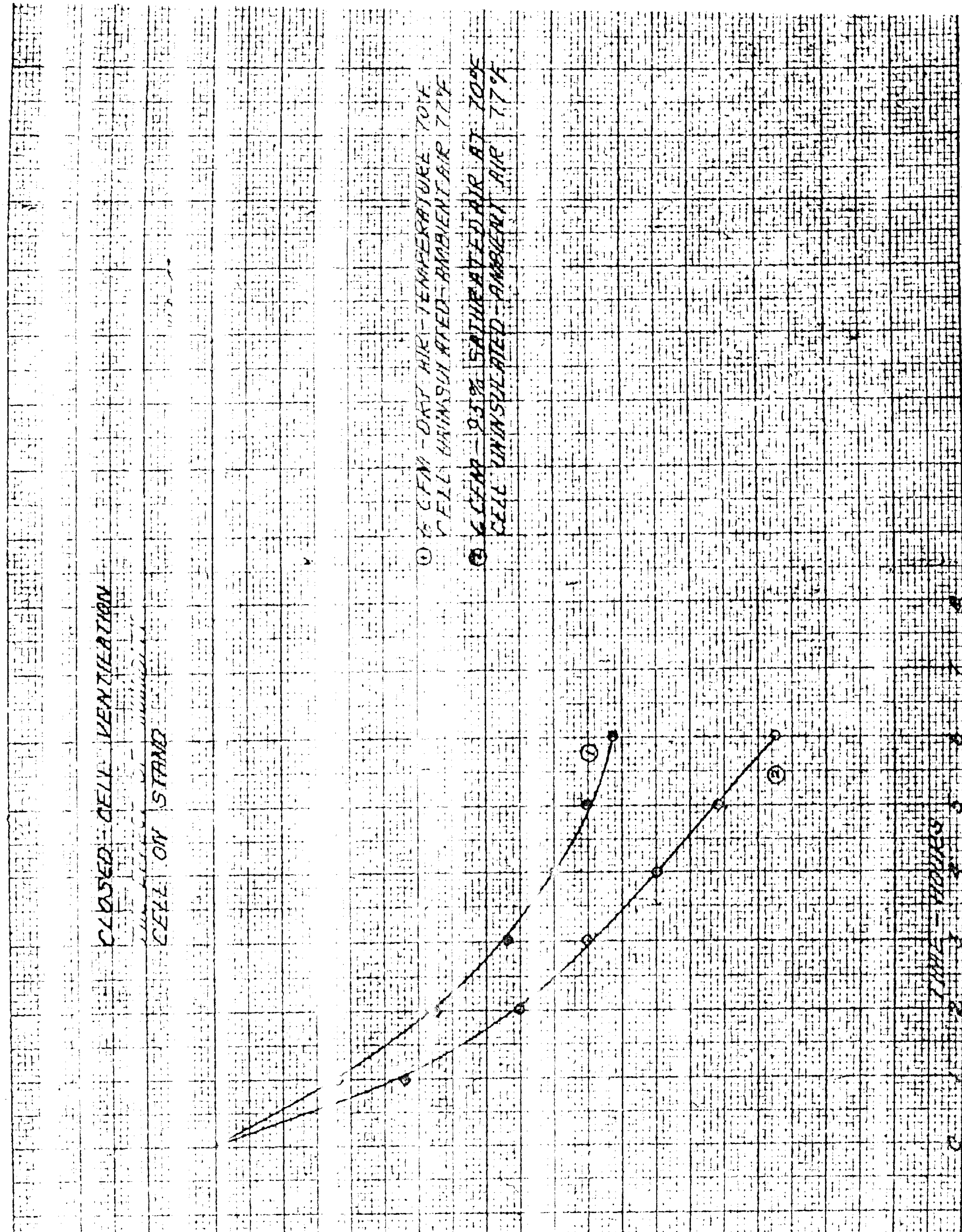

CLOSED-CELL VENTILATION
CELL ON STAND
115
111
99
95
ELECTROLYTE TEMPERATURE (°F)
TIME - HOURS
0 1 2 3 4 5 6 7 8
① 6 CFM - DRY AIR - TEMPERATURE 70°F
CELL UNINSULATED - AMBIENT AIR 77°F
② 6 CFM - 95% SATURATED AIR AT 70°F
CELL UNINSULATED - AMBIENT AIR 77°F

PLATE 20

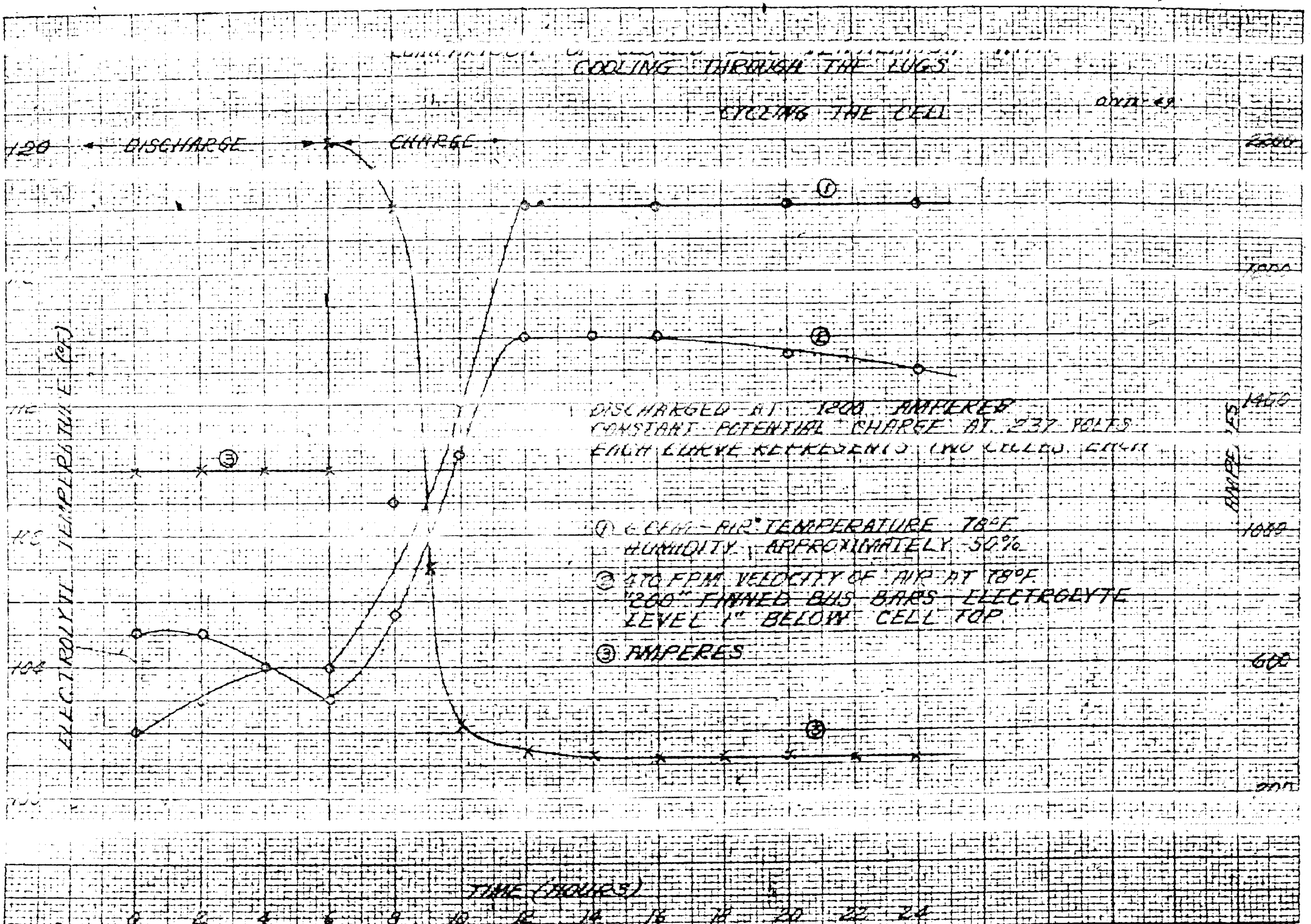

COOLING THROUGH THE LUGS
CYCLING THE CELL
DISCHARGE
CHARGE
DISCHARGED AT 1200 AMPERES
CONSTANT POTENTIAL CHARGE AT 2.37 VOLTS
① AIR TEMPERATURE 78°F
HUMIDITY APPROXIMATELY 50%
② 470 FPM VELOCITY OF AIR AT 78°F
"200" FINNED BUS BARS ELECTROLYTE
LEVEL 1" BELOW CELL TOP
③ AMPERES
ELECTROLYTE TEMPERATURE (°F)
AMPERES
TIME (HOURS)
120
104
2000
1400
1000
600
0
2
4
6
8
10
12
14
16
18
20
22
24

PLATE 21

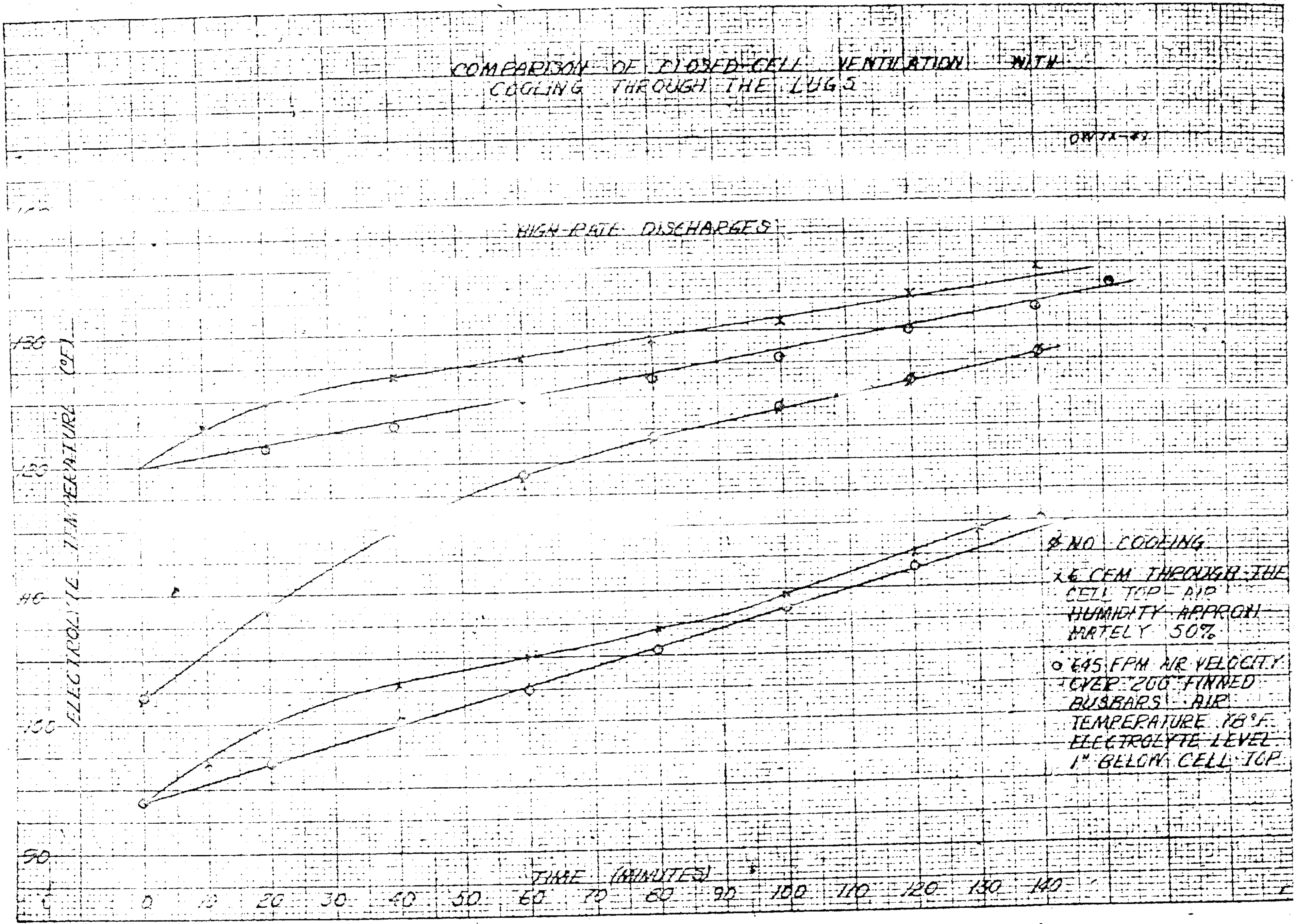
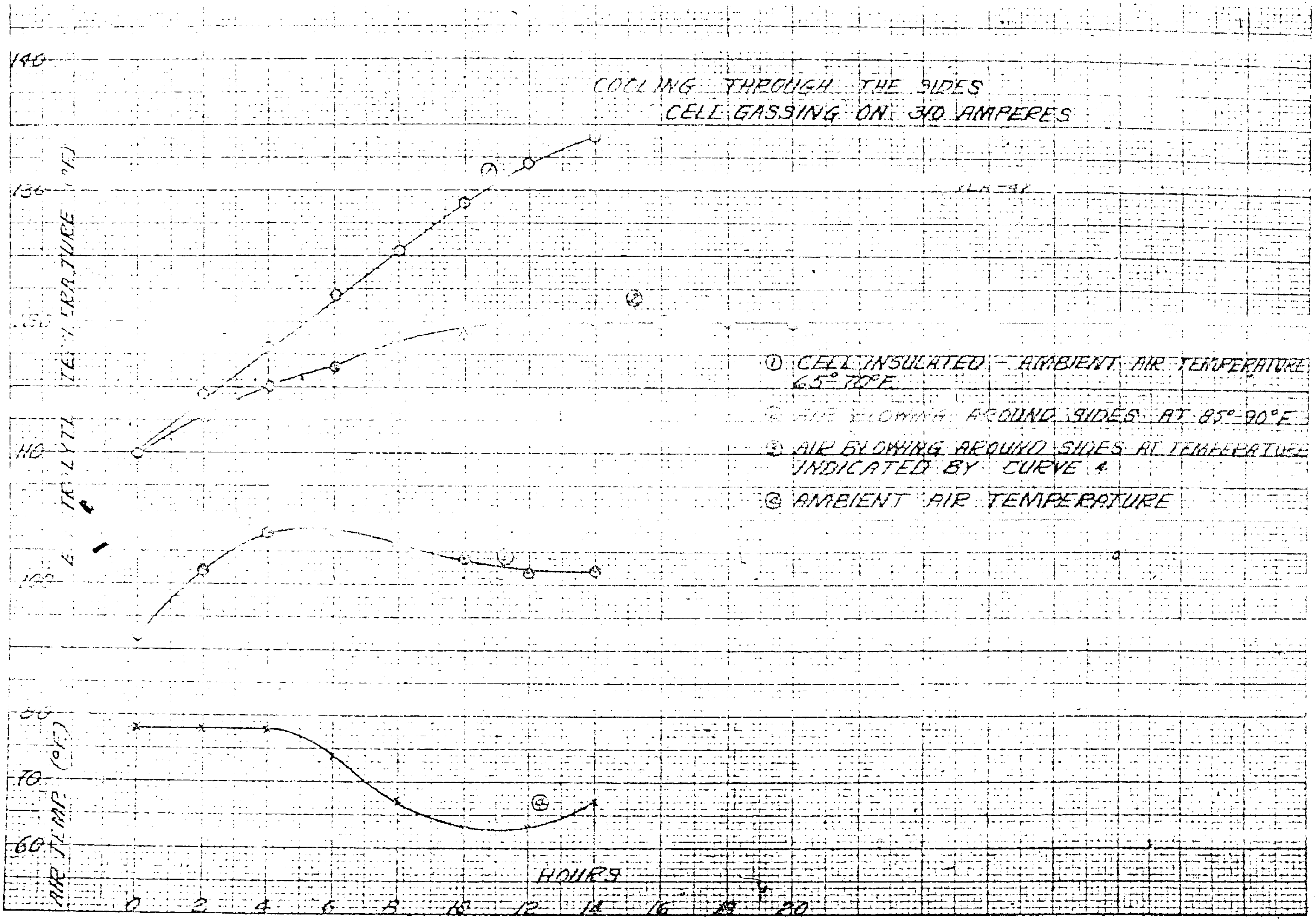

COMPARISON OF CLOSED CELL VENTILATION WITH
COOLING THROUGH THE LUGS
ONTX-43
HIGH-RATE DISCHARGES
ELECTROLYTE TEMPERATURE (°F)
TIME (MINUTES)
0
20
30
40
50
60
70
80
90
100
110
120
130
140
ø NO COOLING
x 6 CFM THROUGH THE CELL TOP AIR HUMIDITY APPROXIMATELY 50%
o 645 FPM AIR VELOCITY OVER 200 FINNED BUSBARS AIR TEMPERATURE 78°F.
ELECTROLYTE LEVEL 1" BELOW CELL TOP

PLATE 22



COOLING THROUGH THE SIDES
CELL GASSING ON 310 AMPERES
① CELL INSULATED - AMBIENT AIR TEMPERATURE 65°-70°F
② AIR BLOWING AROUND SIDES AT 85°-90°F
③ AIR BLOWING AROUND SIDES AT TEMPERATURE INDICATED BY CURVE 4
④ AMBIENT AIR TEMPERATURE
ELECTROLYTE TEMPERATURE (°F)
AIR TEMP (°F)
HOURS
140
130
120
110
100
80
70
60
0
2
4
6
8
10
12
14
16
18
20

PLATE 23

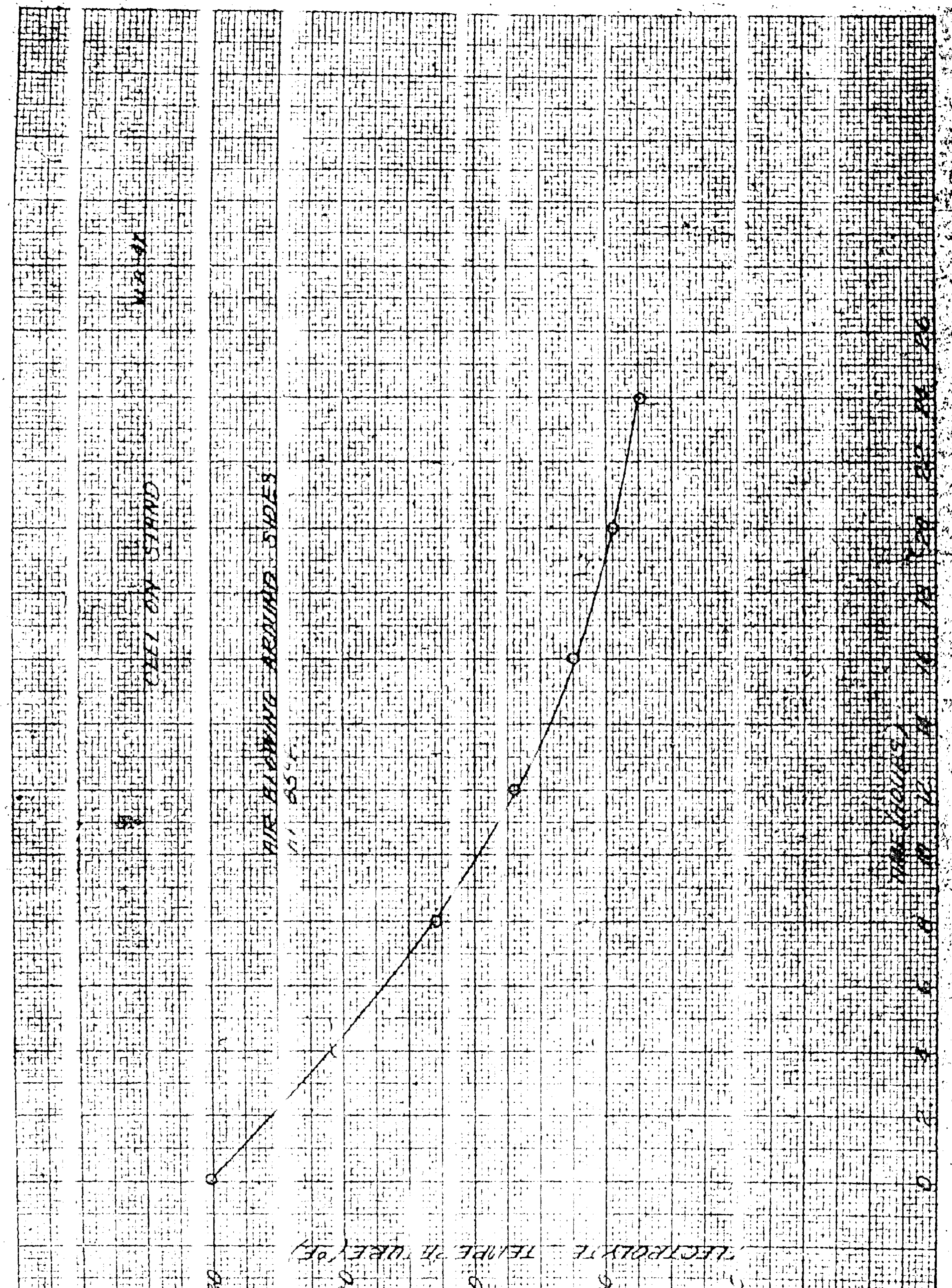

CELL ON STAND
AIR BLOWING AROUND SIDES
TIME (HOURS)
0 2 4 6 8 10 12 14 16 18 20 22 24 26
130
120
110
100

PLATE 24

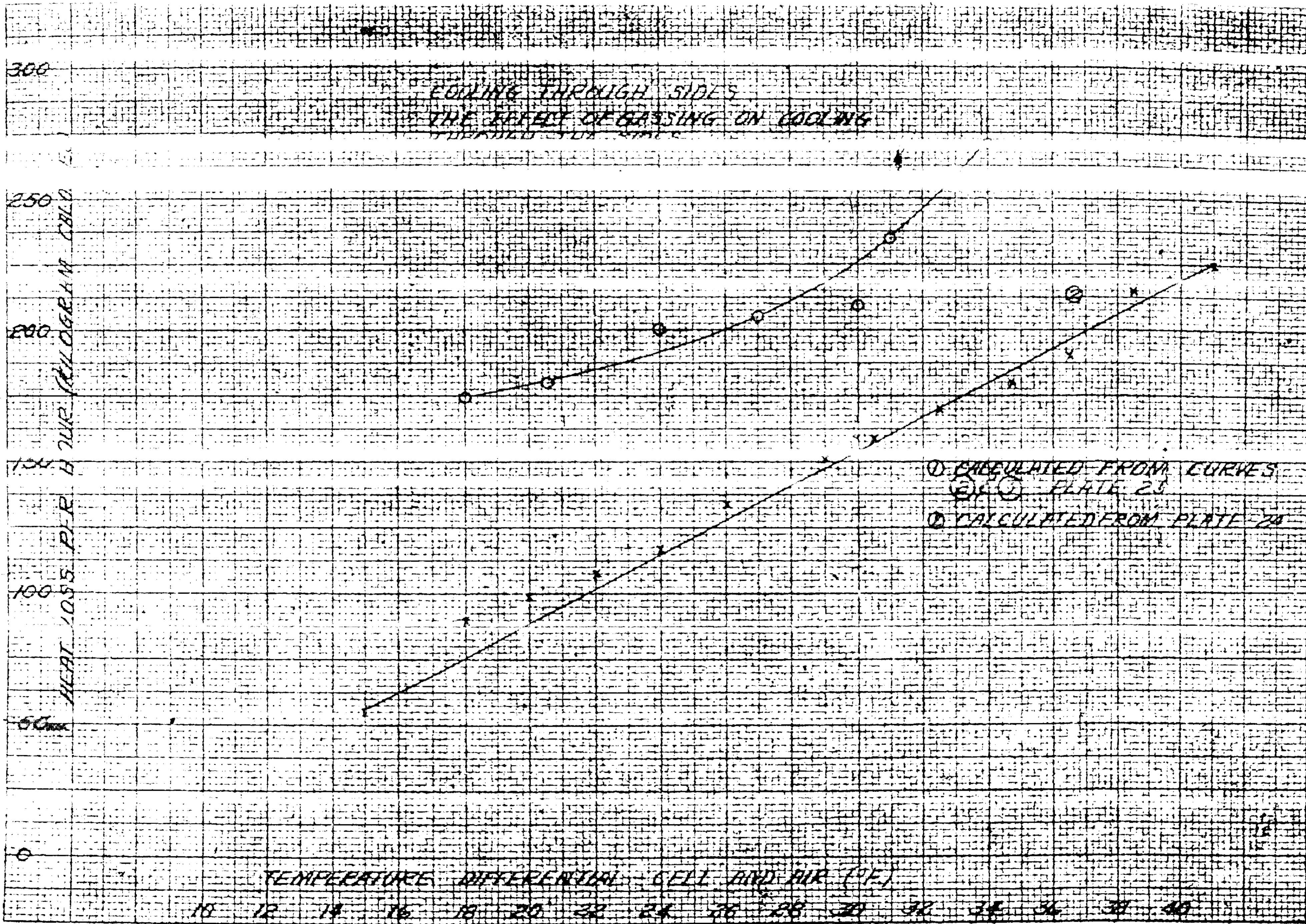

COOLING THROUGH SIDES
THE EFFECT OF GASSING ON COOLING
HEAT LOSS PER HOUR (KILOGRAM CAL
300
250
200
150
100
50
0
① CALCULATED FROM CURVES
PLATE 23
② CALCULATED FROM PLATE 20
TEMPERATURE DIFFERENTIAL CELL AND AIR (°F)
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40

PLATE 25

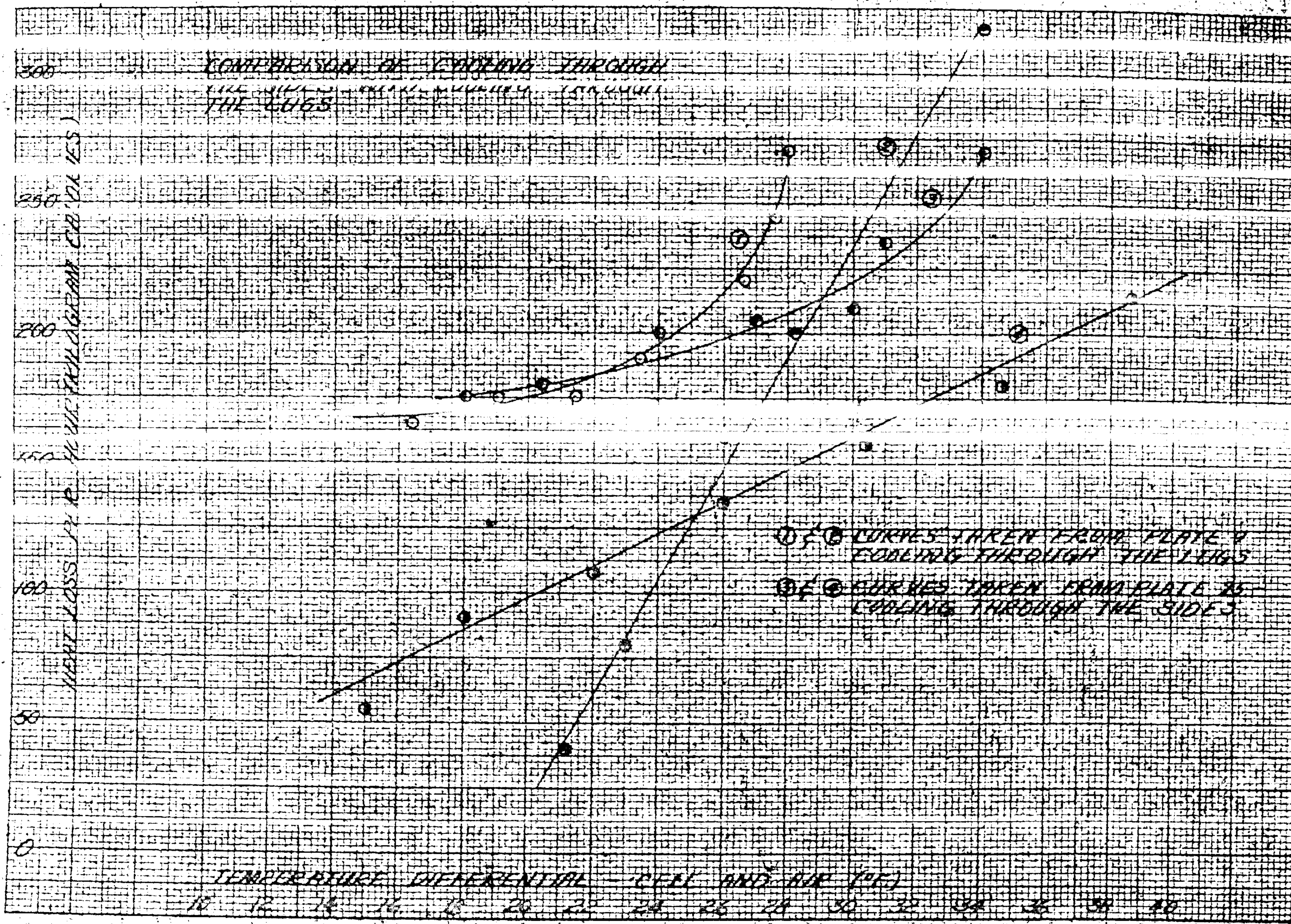

COMPARISON OF COOLING THROUGH
THE LUGS
HEAT LOSS PER HOUR (KILOGRAM CALORIES)
300
250
200
150
100
50
0
TEMPERATURE DIFFERENTIAL - CELL AND AIR (°F)
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
① & ② CURVES TAKEN FROM PLATE 8 COOLING THROUGH THE LUGS
③ & ④ CURVES TAKEN FROM PLATE 35 COOLING THROUGH THE SIDES

PLATE 3

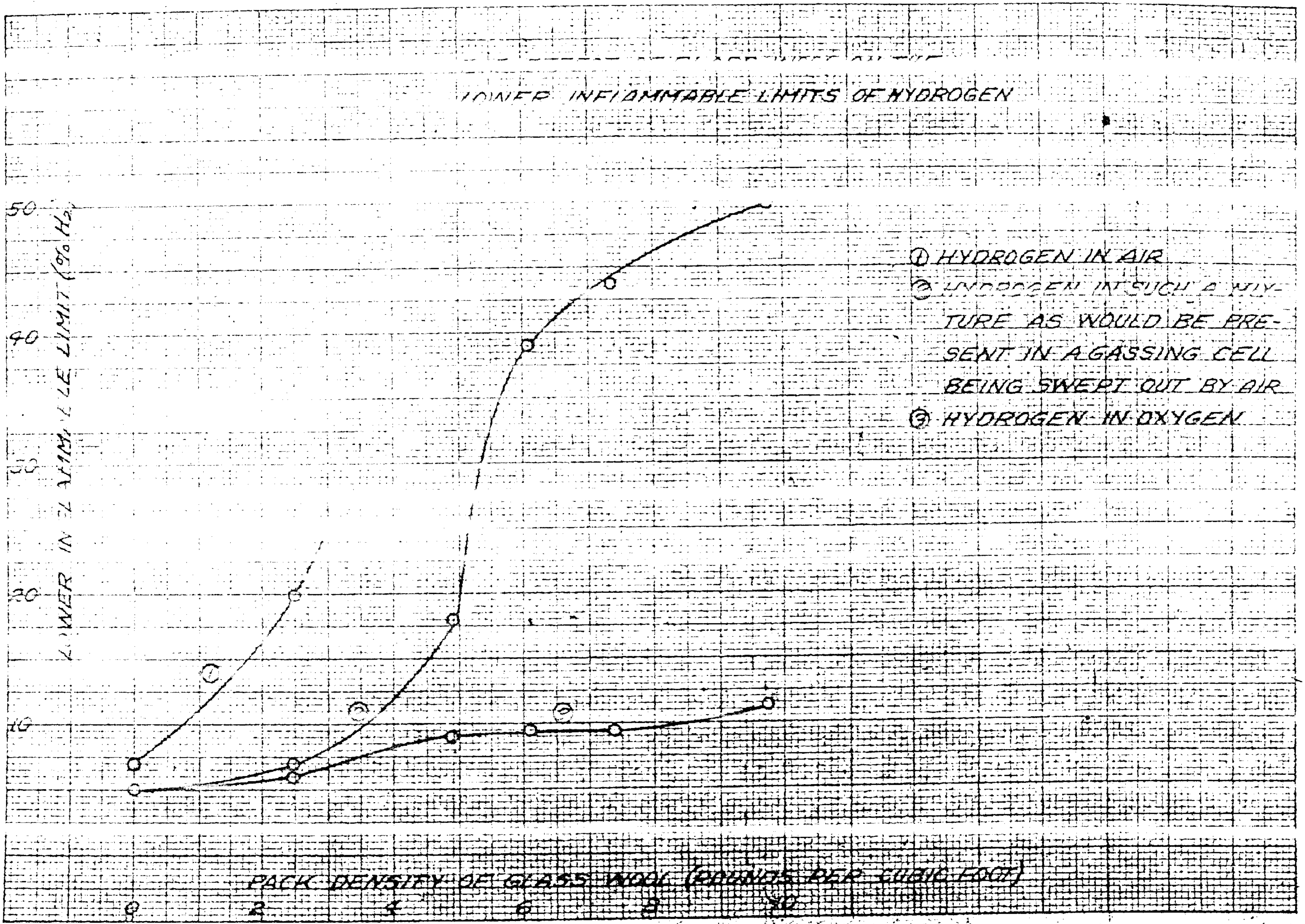

LOWER INFLAMMABLE LIMITS OF HYDROGEN
① HYDROGEN IN AIR
② HYDROGEN IN SUCH A MIX-
TURE AS WOULD BE PRE-
SENT IN A GASSING CELL
BEING SWEPT OUT BY AIR
③ HYDROGEN IN OXYGEN
50
40
30
20
10
0
2
4
6
8
10
PACK DENSITY OF GLASS WOOL (POUNDS PER CUBIC FOOT)

PLATE 27.

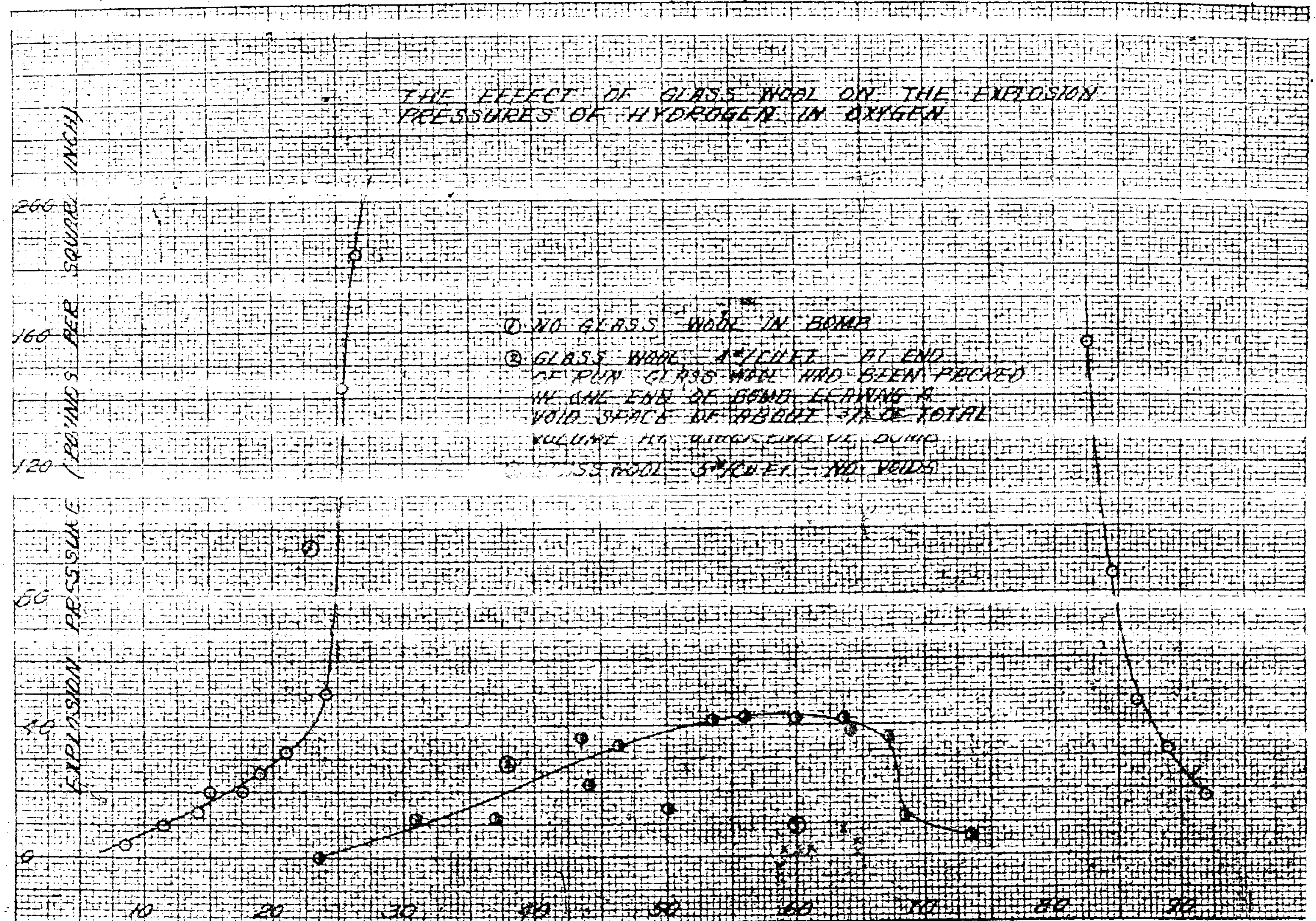

THE EFFECT OF GLASS WOOL ON THE EXPLOSION
PRESSURES OF HYDROGEN IN OXYGEN
① NO GLASS WOOL IN BOMB
② GLASS WOOL 1#/CU.FT. AT END
OF RUN GLASS WOOL HAD BEEN PACKED
IN ONE END OF BOMB LEAVING A
VOID SPACE OF ABOUT 1/3 OF TOTAL
EXPLOSION PRESSURE (POUNDS PER SQUARE INCH)
200
160
120
80
40
0
10
20
30
40
50
60
70
80
90

PLATE 28

DESIGN OF THE AIR FUNNELS
FOR INDUCED VENTILATION

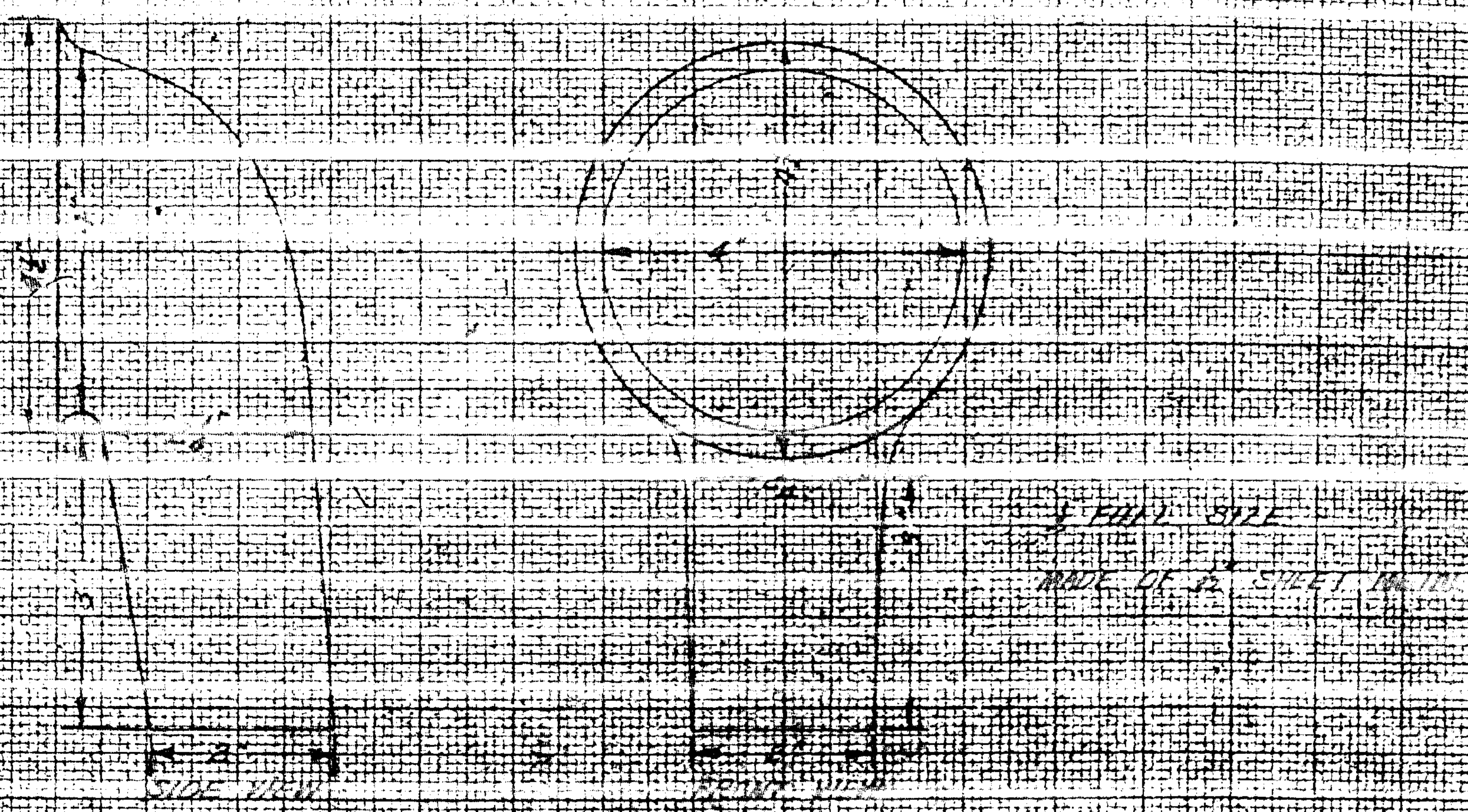


PLATE 29

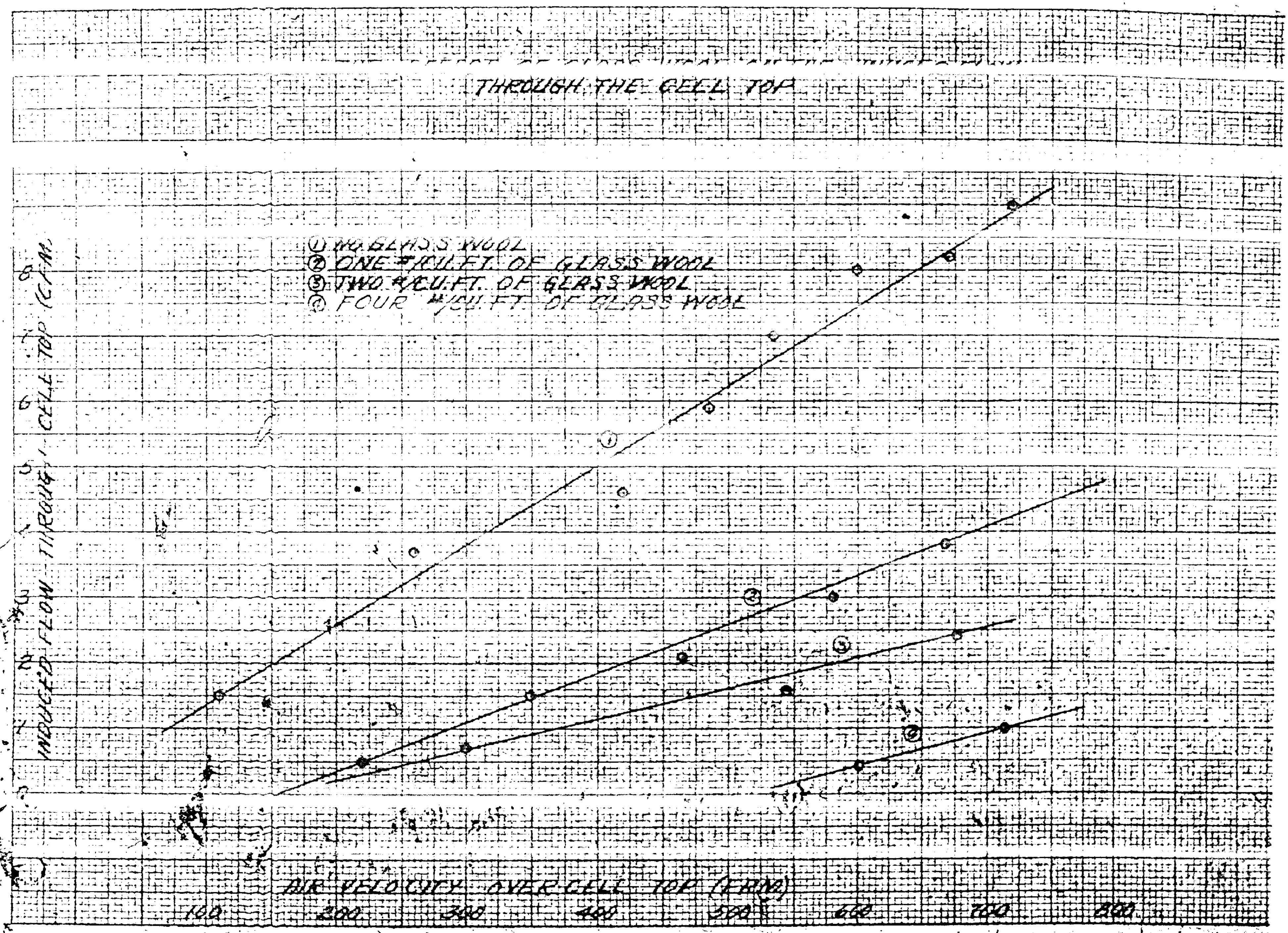

THROUGH THE CELL TOP
① NO GLASS WOOL
② ONE #/CU.FT. OF GLASS WOOL
③ TWO #/CU.FT. OF GLASS WOOL
④ FOUR #/CU.FT. OF GLASS WOOL
INDUCED FLOW THROUGH CELL TOP (CFM)
AIR VELOCITY OVER CELL TOP (FPM)
100
200
300
400
500
600
700
800

PLATE 30